FINAL REPORT

for

MONOPROPELLANT HYDRAZINE THRUSTER SYSTEM

66-R-72

February 12, 1965 through November 27, 1965

Contract No.: NAS 5-9137

Prepared by

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ABSTRACT

This report summarizes a program for the development and delivery to Goddard Space Flight Center of a 0.5 lbf monopropellant hydrazine thruster system intended for use as a laboratory test model. Covered in this report are design and testing of a developmental hydrazine reactor; design, prequalification, testing, and acceptance testing of the complete hydrazine propulsion system including a propellant tank/bellows assembly, propellant valves, lines, filter, and hydrazine reactor.

The hydrazine reactor utilizes Shell 405 spontaneous catalyst for the decomposition of anhydrous hydrazine. The hydrazine reactor is used with a blowdown-pressure feed system providing nominal vacuum total impulse of 350 lbf-sec. Areas of interest in the development of the hydrazine reactor were injection methods, chamber geometry, and catalyst bed packing techniques. During the program approximately 100 tests were conducted in which major effort was placed on injector optimization.

This report is divided into two phases; design and testing. These phases included effort on both the developmental reactor and the end item hardware delivered to Goddard Space Flight Center.

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1.0 INTRODUCTION

This report summarizes eight (8) months of work performed for Goddard Space Flight Center on Contract NAS 5-9137 to develop, test, and deliver a 0.5 lbf thrust monopropellant hydrazine reaction control system. This report consists of a description of the system and its functional specifications and a summary of the design and testing of the system.

The program included design, development, and testing of a prototype reactor which led to the design and manufacture of the end item hardware.

2.0 SYSTEM DESCRIPTION

The propulsion system is basically a pressure-fed monopropellant hydrazine system which operates in the blowdown mode. The engine thrust level varies from 0.5 lbf at the beginning of the mission to 0.33 lbf at the end of the mission. The system consists of two (2) thrust chambers employing the Shell 405 catalyst, two (2) propellant tank/bellows assemblies, two (2) coaxial propellant solenoid valves, four (4) propellant tank isolation valves, two (2) propellant fill valves, two (2) nitrogen pressurization valves, two (2) filter assemblies, a pressure equalization line between the two propellant tank assemblies, and two (2) flexible propellant feed lines from the propellant tank to reactor assemblies. A schematic of the subject system is presented in Figure 1.

The system was designed and qualified to operate under continuous or pulse mode operating conditions based upon the tank/bellows assembly expelling a maximum of 0.75 pounds of propellant in a blowdown configuration with an initial propellant mass flow rate of approximately 0.0022 pounds per second. Pulse mode operation is accomplished at duty cycles of 20% to 100% with pulse widths ranging from 300 milliseconds to 300 seconds over the full blowdown feed pressure range. Thrust chamber catalyst life of 1,500 seconds accumulated burn time was demonstrated during the course of reactor design prequalification.

2.1 System Capabilities

The system capabilities are as follows:

a. Demonstrated operating characteristics as shown in Table I.

b. Capable of being fueled and pressurized as a complete assembly.

c. Man-rated in the fueled and pressurized condition up to 125°F.

2.2 Physical Description

The operating characteristics of the system are summarized in Table II. The system consists of two primary units: the tank/bellows assembly and the reactor assembly which decomposes the monopropellant and produces the desired thrust. The system delivered to Goddard Space Flight Center consisted

PROPULSION SYSTEM
SCHEMATIC

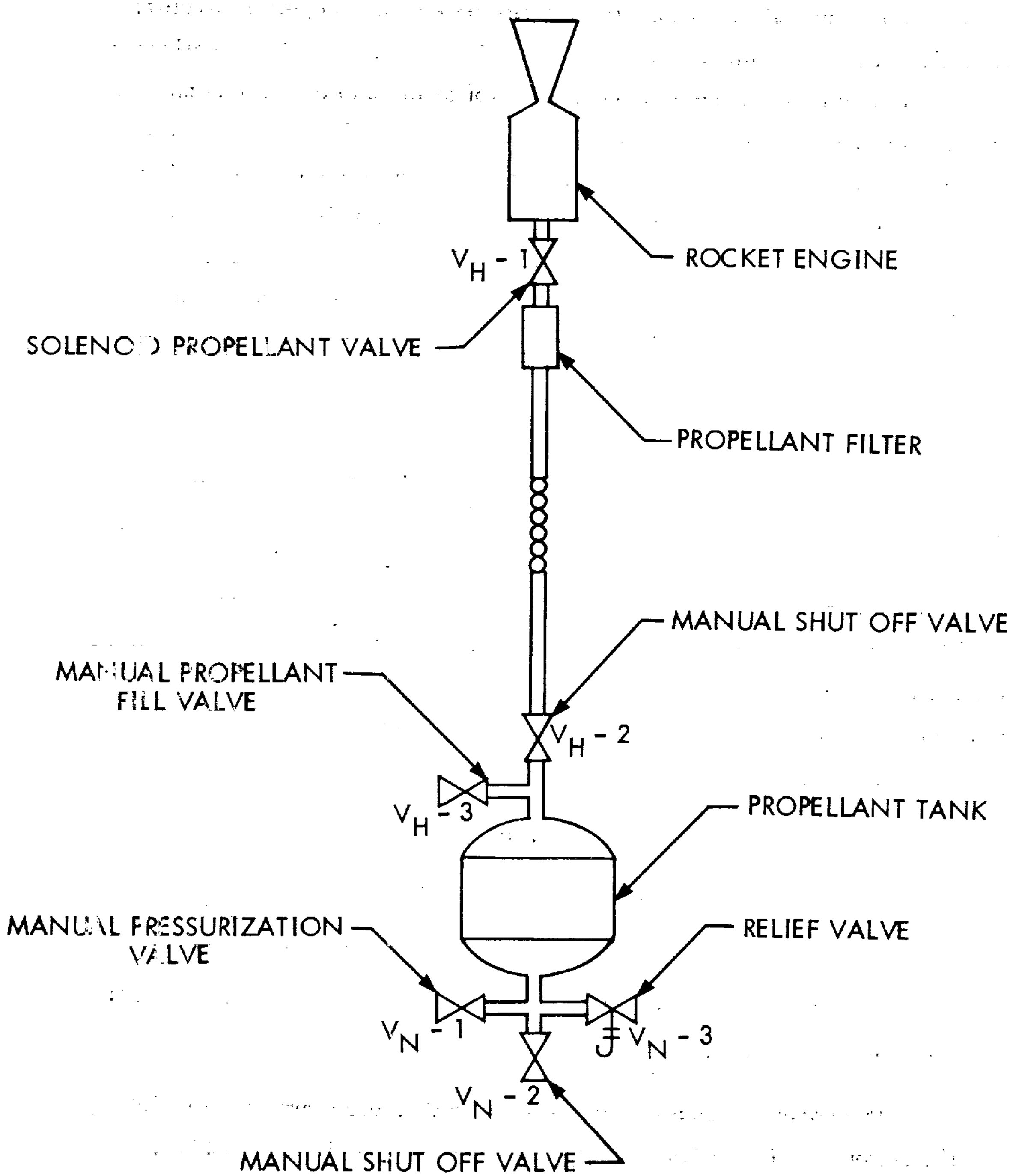


FIGURE 1

TABLE I

DEMONSTRATED CAPABILITIES

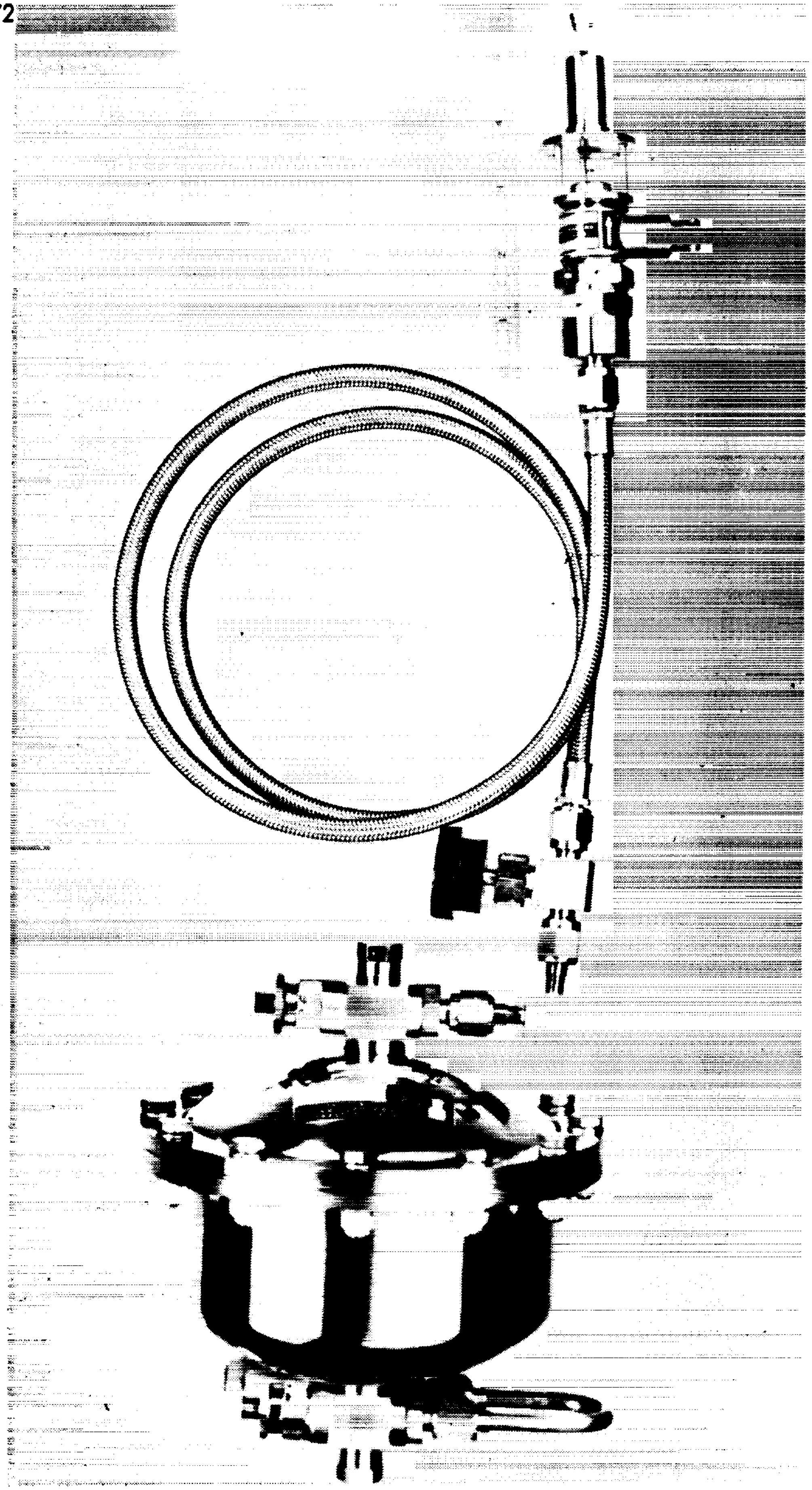
Duty Cycle	20 - 100%
Pulse Widths	300 milliseconds - 300 seconds
Response (to 90% of nominal chamber pressure) hot bed	33 milliseconds
Tail-off (to 10% of nominal chamber pressure)	65 milliseconds
Characteristic velocity, c* (nominal)	4,135 ft/sec
Vacuum Specific Impulse ($\epsilon = 50$)	225 lbf-sec/lbm

TABLE II

SYSTEM OPERATING CHARACTERISTICS

Propellant Tank Pressure, Initial	262 psia
Propellant Tank Pressure, Final	150 psia
Reactor Chamber Pressure, Initial	150 psia
Reactor Chamber Pressure, Final	100 psia
Nozzle Throat Area, A_t	0.00188 in^2
Nozzle Area Ratio, ϵ	50
Nozzle Vacuum Thrust Coefficient, $C_{F_{vac}}$	1.768
Vacuum Thrust, Initial	0.5 lbf
Vacuum Thrust, Final	0.33 lbf

of two (2) complete monopropellant hydrazine propulsion systems shown in Figure 2. The propellant tank/bellows assemblies of the two (2) systems were pressure interconnected for simultaneous blowdown of propellant during operation of the system.



0.5 lbf THRUST MONOPROPELLANT HYDRAZINE PROPULSION SYSTEM

FIGURE 2

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3.0 DESIGN

3.1 Developmental Reactor

The developmental monopropellant hydrazine reactor was designed for 0.5 lbf thrust at altitude with a nozzle area expansion ratio of 50:1 and produced approximately 0.336 pounds of thrust at sea level with a nozzle area expansion ratio of 4:1. The following parametric values were used in the preliminary design evaluation:

F_{vac} (initial vacuum thrust) = 0.5 lbf

$I_{sp_{vac}}$ = 220 lbf/lbm/sec

L* (characteristic chamber length) = 120 inches (empty reactor)

$\epsilon \left(\dfrac{\text{nozzle exit area}}{\text{nozzle throat area}}\right) = 50{:}1$

$P_{c\ initial}$ (initial chamber pressure) = 150 psia

$P_{c\ final}$ (final chamber pressure) = 100 psia

$G \left(\dfrac{\text{initial propellant mass flow rate}}{\text{chamber cross sectional area}}\right) = 0.01\ \text{lbm/sec-in}^2$

The following analysis was used in the design of the developmental reactor:

a. Flow Rate

$I_{sp_{vac}}$ = 220 lbf/lbm/sec

$$\dot{w}_i = \frac{F_{vac}}{I_{sp_{vac}}} = \frac{0.5\ \text{lbf}}{220\ \text{lbf/lbm/sec}} = 0.00227\ \text{lbm/sec}$$

$$\frac{\dot{w}_i}{\dot{w}_f} = \frac{K_1 P_{ci}}{K_1 P_{cf}} = 1.5$$

$$\dot{w}_f = \frac{0.00227}{1.5} \text{ lbm/sec}$$

b. Catalyst Bed Area

Assuming an initial bed loading of .01 lbm/sec-in^2

Then

$$A_b = \frac{\dot{w}_{initial}}{G_{initial}} = \frac{0.00227 \text{ lbm/sec}}{0.01 \text{ lbm/sec-in}^2} = 0.227 \text{ in}^2$$

and

$$D_b = \text{diameter of bed} = 0.538 \text{ inches}$$

c. Thrust Coefficient

$$C_{F(vac)} = \lambda C_d C_{F(opt)} + P_e/P_c \epsilon$$

Where:

$C_{F(vac)}$ = vacuum thrust coefficient

$C_{F(opt)}$ = optimum thrust coefficient for $P_e = P_o$

λ = correction factor for nozzle angle divergence

C_d = discharge coefficient

P_e = nozzle exit pressure

P_c = chamber pressure

ϵ = nozzle expansion area ratio = 50:1

Thrust coefficient and area ratio tables, H. S. Seifert and J. Crum were used in the following calculations:

$$C_{F(vac)} \text{ (no losses)} = 1.82096$$

$$P_e/P_c \epsilon = 0.05664$$

$$C_{F(opt)} = 1.82096 - 0.05664 = 1.76432$$

$$C_{F(vac)} = \lambda C_d \, C_{F(opt)} + P_e/P_c \epsilon$$

$$= (0.970)(1.76432) + (0.05664) = 1.768$$

d. Throat Diameter

$$F_{(vac)} = P_c \, A_t \, C_{F(vac)}$$

Therefore

$$A_t = \frac{F_{(vac)}}{P_c \, C_{F(vac)}} = \frac{0.5 \text{ lbf}}{(150 \text{ lbf/in}^2)(1.768)} = 0.00188 \text{ in}^2$$

and

$$D_t \text{ (throat diameter)} = 0.0489 \text{ inches}$$

e. Chamber Length

L^* = characteristic chamber length = 120 inches

V_c = chamber volume

A_t = nozzle throat area = .00188 in^2

L_c = chamber length

A_b = cross sectional area of bed

$L^* = V_c/A_t$

Therefore:

$$V_c = L^* A_t = (120 \text{ in})(.00188 \text{ in}^2) = .226 \text{ in}^3$$

$$L_c = V_c/A_b = \frac{.226 \text{ in}^3}{.227 \text{ in}^2} = 1.0 \text{ inches}$$

f. Nozzle Exit Area

$$\epsilon = \frac{\text{exit area}}{\text{throat area}} = 50{:}1$$

$$\epsilon = \frac{K_1 D_e^{\,2}}{K_1 D_t^{\,2}};\ D_e = \text{exit diameter} = D_t\sqrt{50} = .345 \text{ in.}$$

g. Propellant Tank Pressure

P_{ci} = initial chamber pressure = 150 psi

P_{cf} = final chamber pressure = 100 psia

$P_c = K_1 \dot{w}$

Where:

K_1 = constant = $c^*/A_t\, g$

g = gravitational constant

Letting ΔP_T = tank pressure - chamber pressure = $K_2 \dot{w}^2/\rho$

Where:

K_2 = constant

ρ = propellant density = constant

Therefore:

$$\frac{\Delta P_{Ti}}{\Delta P_{Tf}} = \frac{\dot{w}_i^{\,2}}{\dot{w}_f^{\,2}} = (1.5)^2 = 2.25$$

If:

$$P_{Tf} = 50 \text{ psid}$$

Then:

$$P_{Ti} = (2.25 (50) = 112.5 \text{ psid}$$

And:

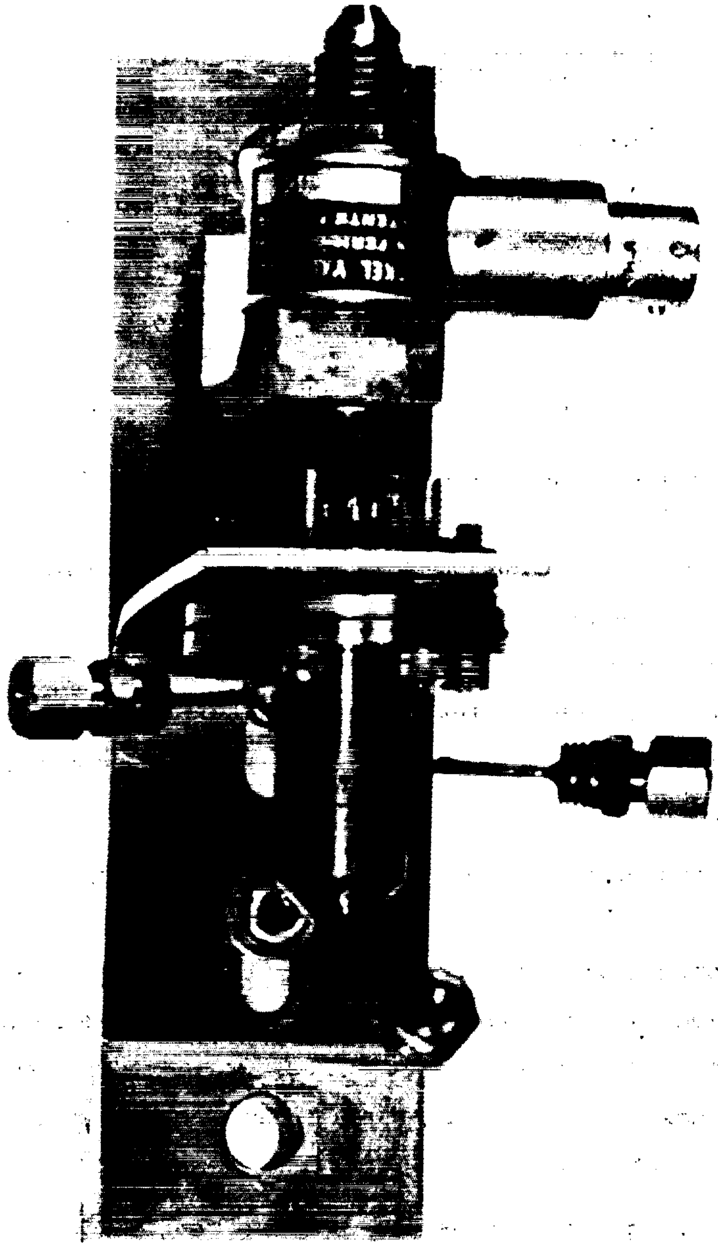
$$P_{Ti} = 150 + 112.5 = 262.5 \text{ psia}$$

$$P_{Tf} = 100 + 50 = 150 \text{ psia}$$

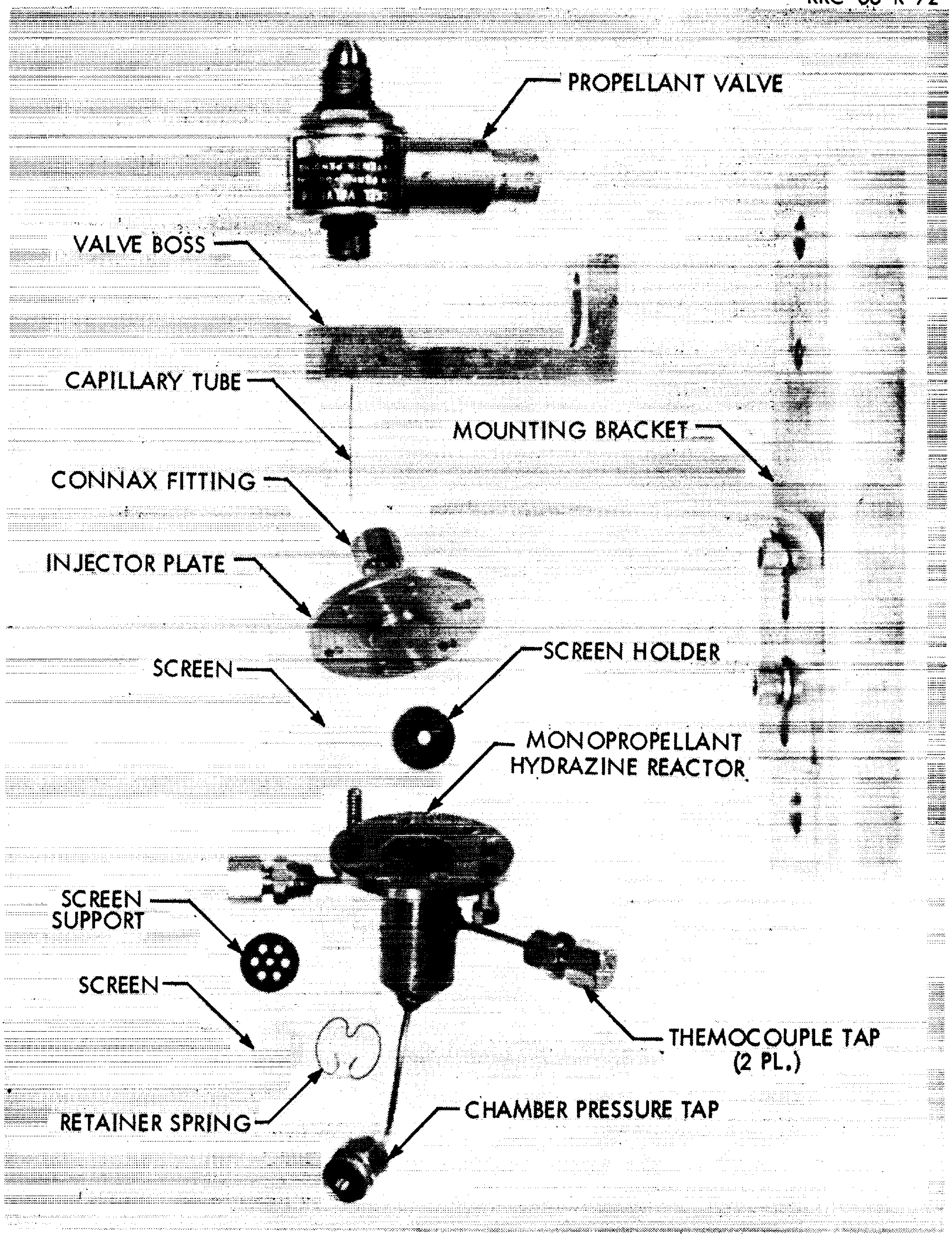
Initial design of this developmental reactor incorporated a 0.010 inch I.D. capillary tube for injection of the hydrazine propellant into 20 to 30 mesh Shell 405 spontaneous catalyst. The chamber was instrumented with two thermocouples and a pressure transducer to measure downstream stagnation chamber pressure. The thermocouples were of the immersion type and extended into the catalyst bed. They were located approximately at the top of the bed and the center of the bed. Figure 3 shows the developmental reactor and valve.

Manufacture of the development reactor consisted mainly of fabrication of a chamber/nozzle assembly, an injector head, screen support, screens, an injector, and valve boss. Figure 4 shows an exploded view of the reactor, propellant on-off valve, and mounting bracket. The capillary tube was brazed into the valve boss and was connected to the injector plate by means of a conax fitting which allowed the depth of the capillary tube into the chamber to be varied.

During testing of the developmental reactor several modifications were made to the injection system. One modification was to incorporate an electrolytic perforated plate in the injector design. The injector plate was recessed and undercut to accept a plate .200 inches in diameter, and with various thicknesses, hole diameters, and percent open area.



0.5 lbf THRUST DEVELOPMENT REACTOR



EXPLODED VIEW
0.5 lbf THRUST DEVELOPMENT REACTOR,
VALVE, AND MOUNT

12096

FIGURE 4

The perforated plate was placed in the undercut and the face material was rolled over to seal and hold the plate. The final injector configuration used on the developmental program consisted of an injector plate with the capillary tube and an orifice plate with a manifold .050 inches in diameter by .010 inches deep and five (5) orifices .005 - .006 inches in diameter. An asbestos type gasket was used to seal the orifice plate on the combustion chamber side and an "O"-ring was used on the propellant side.

3.2 End Item Hardware

3.2.1 Overall System

The propulsion system delivered to Goddard Space Flight Center is a laboratory test system sized to meet typical low thrust attitude control requirements. This system consists of two (2) complete primary monopropellant hydrazine thruster systems with interconnecting propellant tanks to permit simultaneous propellant blow down. The complete delivered system includes the following items:

a. Positive expulsion tank/bellows assemblies, (2).

b. Propellant fill valves, (2).

c. Propellant pressurization valves, (2).

d. Propellant tank isolation valves, (4).

e. Propellant feed lines, (2).

f. Propellant filters, (2).

g. Propellant on/off valves, (2).

h. Hydrazine reactor assemblies, (2).

3.2.1.1 Performance Characteristics

Vacuum thrust (initial), lbf	0.50
Vacuum thrust (final), lbf	0.33
Chamber Pressure (initial), psia	150

Chamber pressure (final), psia	100
Vacuum thrust coefficient	1.768
Vacuum specific impulse, lbf-sec/lbm	225
Propellant flow rate (initial), lbm/sec	0.0022
Propellant flow rate (final), lbm/sec	0.0018

3.2.1.2 System Weights

Combustion chamber and nozzle (1), lbm	0.03
Injector (1), lbm	0.10
Catalyst, lbm	0.01
Propellant line (1), lbm	0.15
Fill valve (1), lbm	0.10
Pressurization valve (1), lbm	0.10
Manual valves (2), lbm	0.54
Fittings (5), lbm	0.43
Relief valve (1), lbm	0.16
Filter (1), lbm	0.24
Propellant Valve (1), lbm	0.16
Tank/bellows assembly (1), lbm	5.65

Total Primary System Weight (1), lbm = 7.67

3.2.2 System Components

3.2.2.1 Propellant Tank Bellows Assembly

The propellant tank bellows assembly is a positive expulsion device consisting of a tank and a bellows both constructed of 347 stainless steel and manufactured by the Metal Bellows Corporation, Los Angeles, California. This tank is designed to hold and expel approximately .75 pounds of propellant in a blowdown mode with an initial tank pressure of 265 psia and a final tank pressure of 150 psia. Figure 5

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D

1. REMOVE ALL BURRS & SHARP EDGES.
2. INTEREPRET DRAWING PER DOCUMENTS REFERENCED IN MIL-D-70327.
3. ONLY THE ITEMS DESCRIBED ON THIS DRAWING WHEN PROCURED FROM THE VENDOR LISTED HEREON IS APPROVED BY ROCKET RESEARCH CORP. FOR USE IN THE APPLICATION SPECIFIED HEREON. A SUBSTITUTE ITEM SHALL NOT BE USED WITHOUT PRIOR TESTING & APPROVAL BY ROCKET RESEARCH CORP. OR THE GOVERNMENT PROCURING ACTIVITY.
4. TANKS TO BE SERIALIZED CONSECUTIVELY FROM 01.
5. DESIGN DATA:
   A TEMPERATURE: OPERATING 0° F TO 120°F
   STORAGE -65°F TO +165°F

   B PRESSURE REQUIREMENTS:

	BELLOWS:(EXTERNAL)	CASE
OPERATING	150 PSI MAX	275 PSI MAX
PROOF	225 PSI MAX	413 PSI MAX
BURST		850 PSI MAX

   C. LEAKAGE:
   1×10^{-7} CC/SEC OF He AT ONE ATMOSPHERE (INTERNAL)
   1×10^{-7} CC/SEC OF He AT ONE ATMOSPHERE (EXTERNAL)

   D. OPERATING MEDIA:
   HYDRAZINE ON SIDE "A"
   N_2 ON SIDE "B"

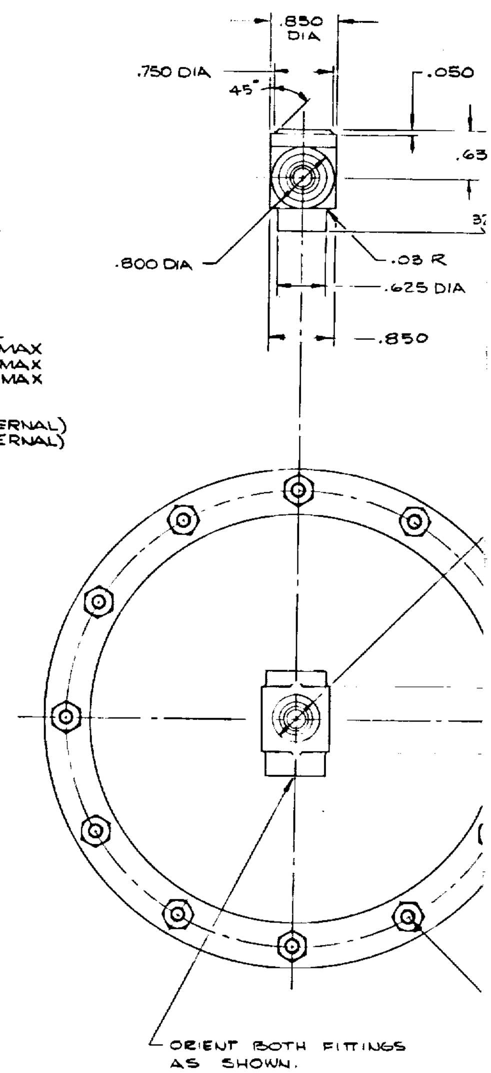
C

   E. OPERATING PARAMETERS:
   CHARGE SIDE "B" WITH 262 PSIA AND SIDE "A" FILLED WITH HYDRAZINE. SIDE "B" PRESSURE = 150 PSIA APPROX WHEN 21 IN^3 FLUID IS DISCHARGED FROM SIDE "A".

   F. SERVICE LIFE: 5000 CYCLES

   G. COMPATIBILITY:
   ALL MATERIALS CONTACTING THE FLUID (SIDE A) TO BE COMPATIBLE WITH HYDRAZINE (N_2H_4). TANK TO BE CRES 347 & THE BELLOWS TO BE AM 350. "O" RINGS TO BE PARKER BUTYL COMPOUND 37-014.

   H. BELLOWS:
   O. D. 4.98 INCHES
   I. D. 4.00 INCHES
   EFFECTIVE AREA 15.79 $IN.^2$
   STROKE 1.33 INCHES
   Δ VOLUME $\sim$ 21 $IN.^3$



B

A

APPROVED SOURCES OF	
VENDOR & VENDORS PART NO.	AP
METAL BELLOWS CORP. PACIFIC DIVISION 20977 KNAPP ST. CHATSWORTH, CALIF. PART NO.: 57263	PROPELLAN MONOPROPE

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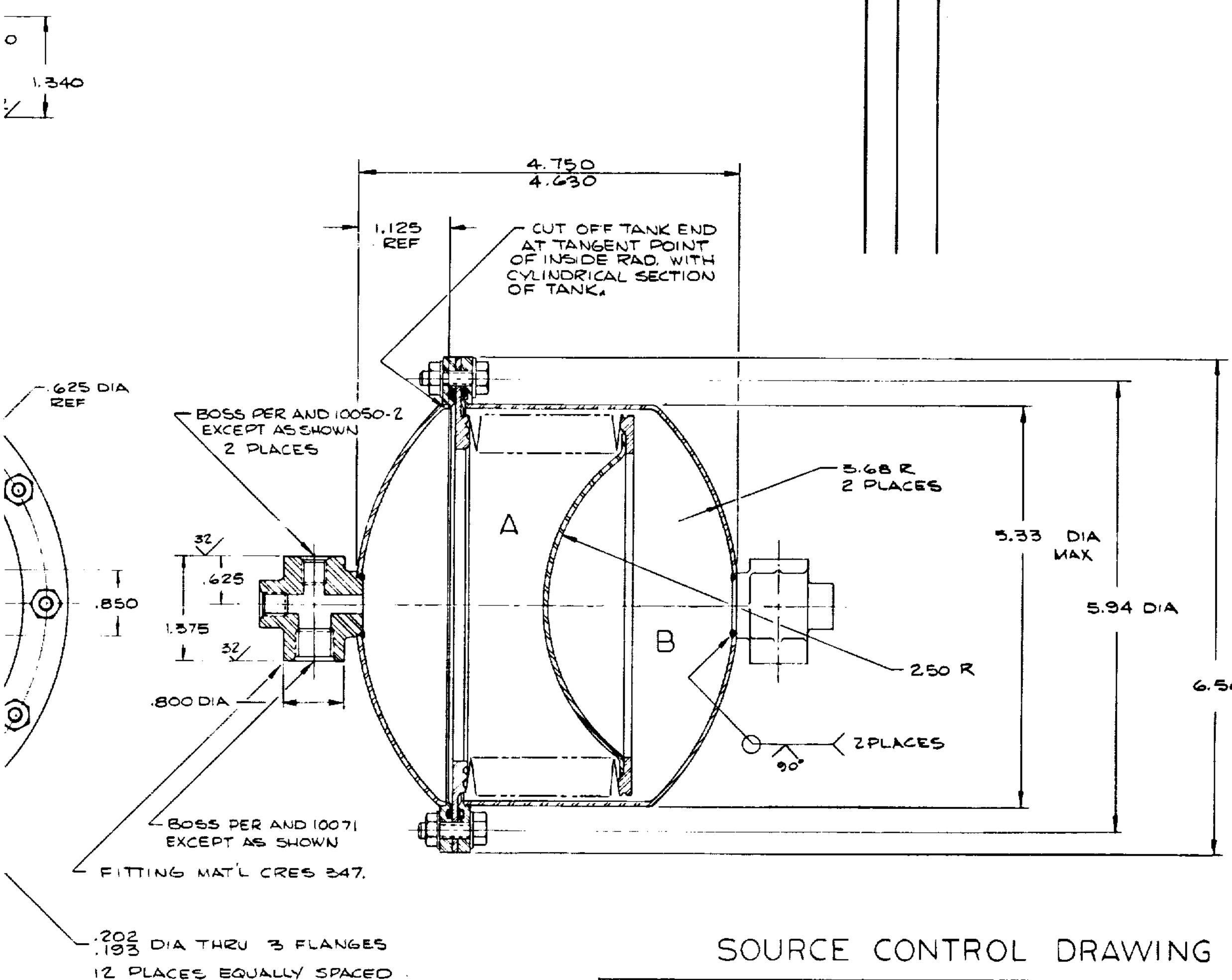

SOURCE CONTROL DRAWING

SYM	CODE IDENT. NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	UNIT WT	ZONE	ITEM NO.

LIST OF MATERIALS

... SUPPLY
...PLICATION
...T EXPULSION — ...LLANT PROPULSION SYSTEM

WORK CHARGE NO. 171-28

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
DECIMAL TOLERANCE .XX ± .03 .XXX ± .010
ANGULAR TOLERANCE ± 1/2°
DO NOT SCALE DRAWING

DRAWN	JACOBSEN	5-16-65
CHECKED	H.A.A.	6/1/65
	K. Adams	6/1/65

ROCKET RESEARCH CORPORATION, SEATTLE, WASHINGTON

TITLE: EXPULSION TANK

CODE IDENT. NO. 21562 — DWG SIZE D — DWG NO. 24191

SCALE 1/1 — RELEASE DATE 6-1-65 — SHEET 1 OF 1

DWG LEVEL 1

FIGURE 5

depicts the propellant tank assembly and summarizes the tank specifications.

3.2.2.2 Propellant Valve

The propellant valves employ a teflon soft seat and are a model AF 77C-B41 coaxial solenoid operated valve manufactured by the Eckel Valve Company. The source control drawing for the propellant valve presented in Figure 6 summarizes the valve specifications.

3.2.2.3 Propellant Filter

The filter used in this system is a pleated disc type filter with a nominal filtration rating of 10 microns and an absolute rating of 25 microns manufactured by Aerospace Components Corporation.

3.2.2.4 Fill and Pressurization Valves

The gas pressurization and the hydrazine fill valves are a standard MS 28889 valve.

3.2.2.5 Manual Shutoff Valves

The manual shutoff valves are a 1/4 inch needle valve manufactured by the Dragon Engineering Company. This model 3000 valve utilizes a teflon seat and has an orifice of 0.170 inches.

3.2.3 Hydrazine Reactor

Data obtained from a testing program designed to optimize the developmental reactor produced the reactor design depicted in Figure 7. This hydrazine reactor consists of two main parts, the injector assembly and the chamber/nozzle assembly.

The injector assembly consists of a valve boss, capillary tube, chamber adapter, orifice plate, and three structural thermal spacers.

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1. Only the item described on this drawing when procured from the vendor(s) listed hereon is approved by Rocket Research Corp., for use in the application(s) specified hereon. A substitute item shall not be used without prior testing and approval by Rocket Research Corp., or by the Government Procuring Activity.

2. TEMPERATURE RANGE

   Ambient -65°F to +165°F
   Effluent -65°F to +165°F

3. PRESSURES

   Operating 0 to 275 psig
   Proof 525 psig
   Burst 875 psig

4. LEAKAGE

   Internal: 1 drop (max) per 3 minutes @ 350 psig H_2O
   External: None from 0 to 525 psig

5. FLOW CHARACTERISTICS

   Equivalent orifice .030 diameter where c_d = .65 (REF)

6. EFFLUENT

   Hydrazine (N_2H_4)

7. ELECTRICAL

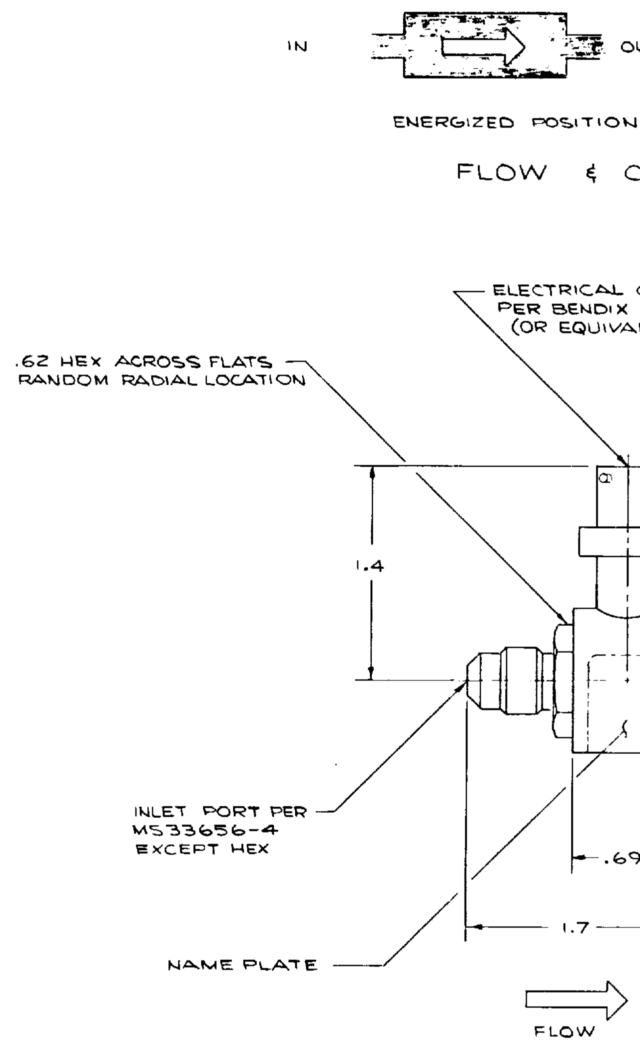
   Volts: 18 to 30 D.C.
   Duty: Continuous
   Power: 2 watts (max) @ 24 V @ 70°F
   Solenoid: Explosion proof
   Connector: Bendix PT1H-8-2P (or equivalent)

8. QUALIFIED

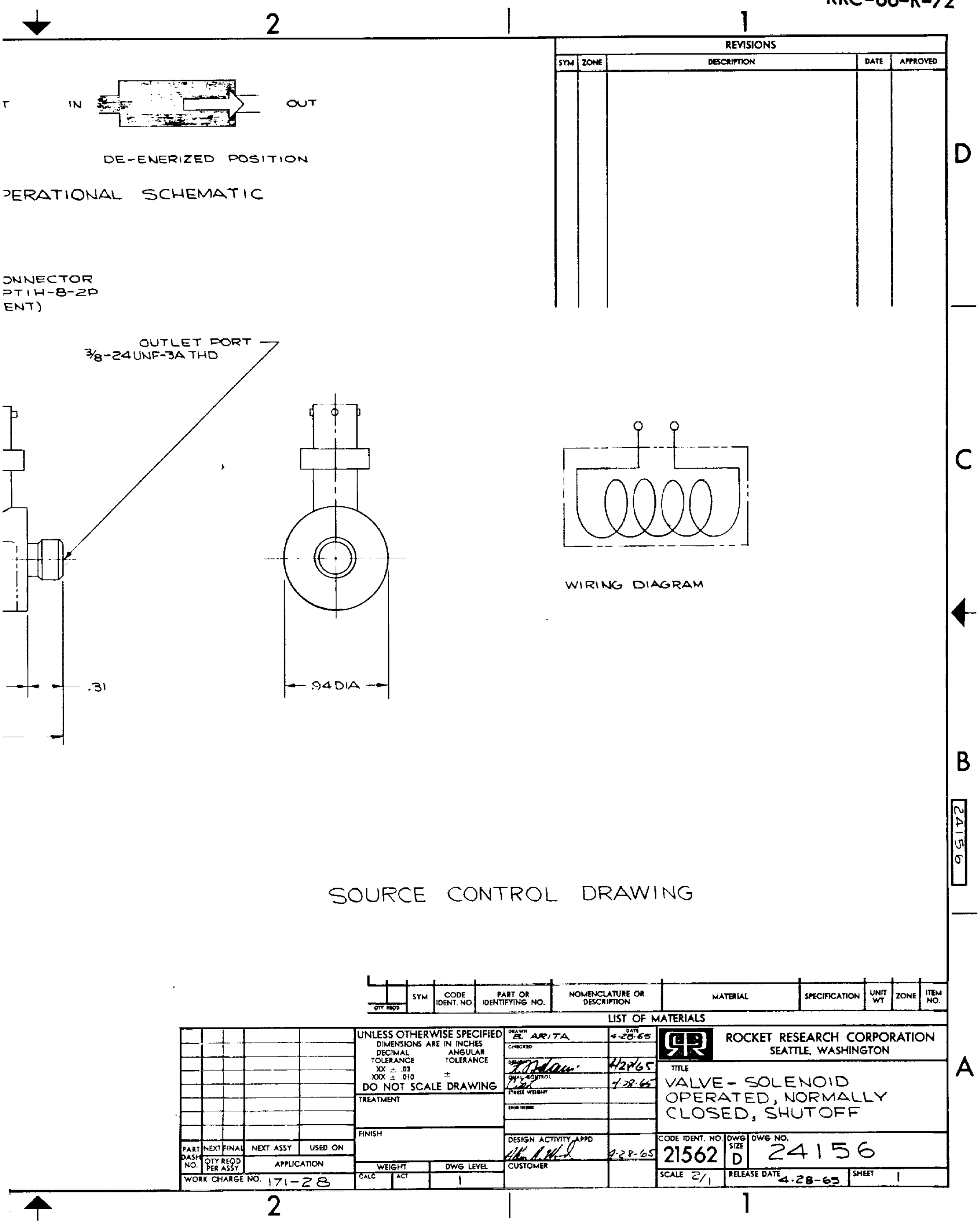
   To requirements of MIL-S-4040A except Paragraph 3.3.1 (solenoid temperature rise) does not conform.

9. MATERIALS

   All internal parts in contact with effluent are compatible with N_2H_4



APPROVED SOURCES OF SUPPLY	
VENDOR & VENDORS PART NO.	APPLICATION
ECKEL VALVE CO. SAN FERNANDO, CALIF. PART NO.: AF 77C-B41	PROPELLANT SHUTOFF VALVE IN MONOPROPELLANT HYDRAZINE CONTROL ROCKET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REVISIONS
SYM
ZONE
DESCRIPTION
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DE-ENERIZED POSITION
PERATIONAL SCHEMATIC
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PTIH-8-2P
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WIRING DIAGRAM
D
C
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24156
SOURCE CONTROL DRAWING
QTY REQD
SYM
CODE IDENT. NO
PART OR IDENTIFYING NO.
NOMENCLATURE OR DESCRIPTION
MATERIAL
SPECIFICATION
UNIT WT
ZONE
ITEM NO.
LIST OF MATERIALS
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
DECIMAL TOLERANCE
XX ± .03
XXX ± .010
ANGULAR TOLERANCE
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DO NOT SCALE DRAWING
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QUAL CONTROL
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STRESS WEIGHT
ENGINEER
DESIGN ACTIVITY APPD
4-28-65
CUSTOMER
ROCKET RESEARCH CORPORATION
SEATTLE, WASHINGTON
TITLE
VALVE - SOLENOID OPERATED, NORMALLY CLOSED, SHUTOFF
CODE IDENT. NO.
21562
DWG SIZE
D
DWG NO.
24156
SCALE
2/1
RELEASE DATE
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PART DASH NO.
NEXT
FINAL
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USED ON
APPLICATION
WORK CHARGE NO.
171-28
WEIGHT
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DWG LEVEL
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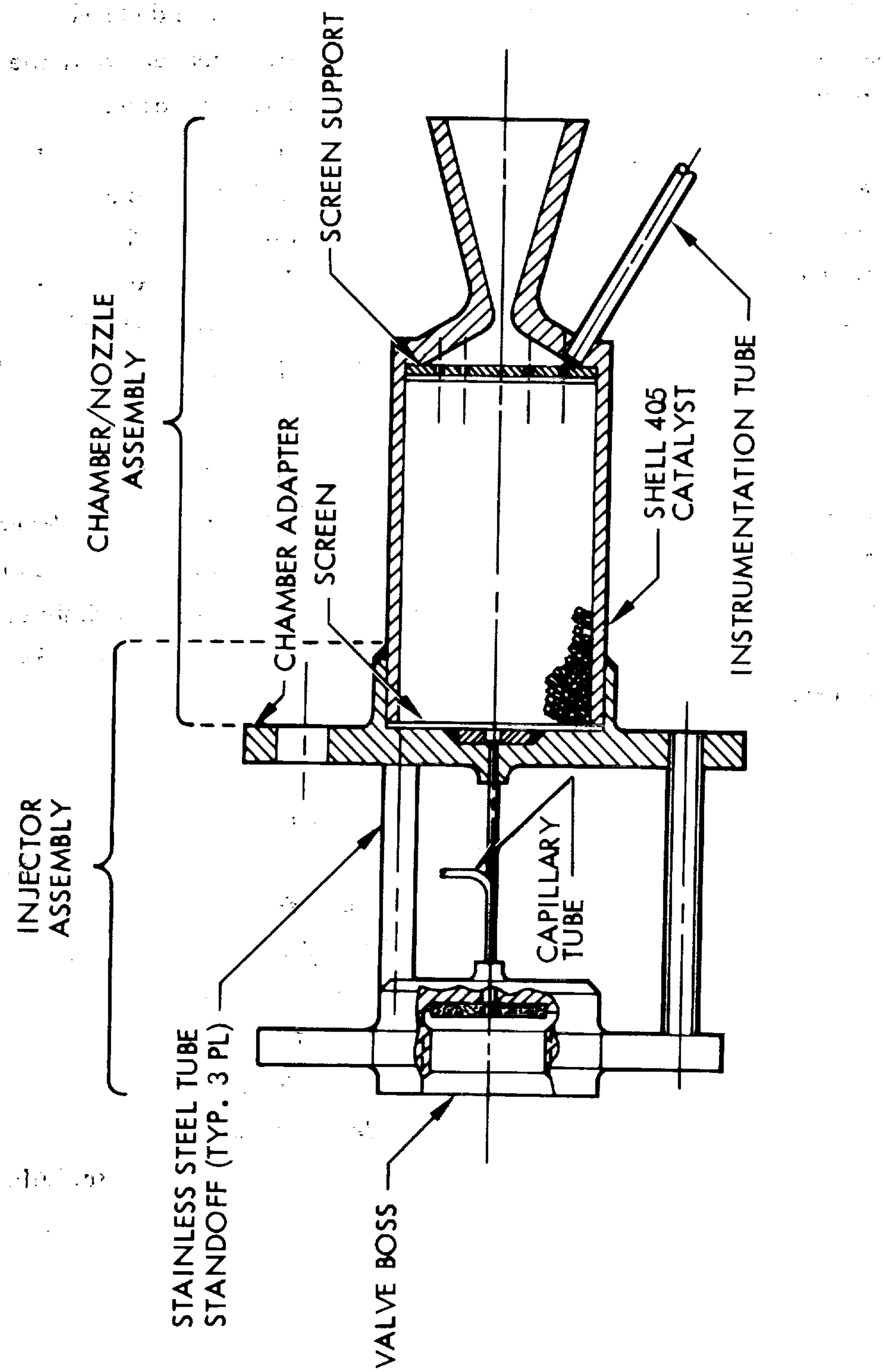
FIGURE 6



.5 lbf MONOPROPELLANT HYDRAZINE REACTOR

The capillary tube is an inconel 600 tube 0.026" x 0.007" wall which contains a half helix and is brazed to the valve boss and chamber adapter. The chamber adapter and valve boss are connected by the three structural stainless steel spacers which also serve as valve thermal stand-offs. The capillary tube feeds an orifice plate that contains a manifold 0.050 inches in diameter by 0.010 inches deep with five orifices 0.006 inches in diameter. This injector configuration minimizes heat conduction from the decomposition chamber to the valve boss valve seat area while permitting differential thermal expansion between the capillary feed tube and the thermal stand-offs (3).

The chamber/nozzle assembly is machined from Haynes Alloy No. 25 with a nominal wall thickness of 0.020 inches. Haynes Alloy No. 25 was used because of its high strength at temperature and resistance to nitriding. The nozzle section has an included angle of convergence of 120° and a half angle of divergence of 15° with an expansion area ratio of 50:1. Figure 8 shows the reactor.

3.2.3.1 Design Characteristics

Throat diameter, D_t, inches	0.049
Throat area, A_t, square inches	0.00188
Contraction 1/2 angle, degrees	60
Expansion area ratio, A_e/A_t	50:1
Exit diameter, D_e, inches	0.348
Expansion 1/2 angle, degrees	15
Characteristic length (empty), L* in.	120
Chamber diameter, D_c, inches	0.538
Cooling technique	Radiation

0·5 lbf THRUST MONOPROPELLANT HYDRAZINE REACTOR

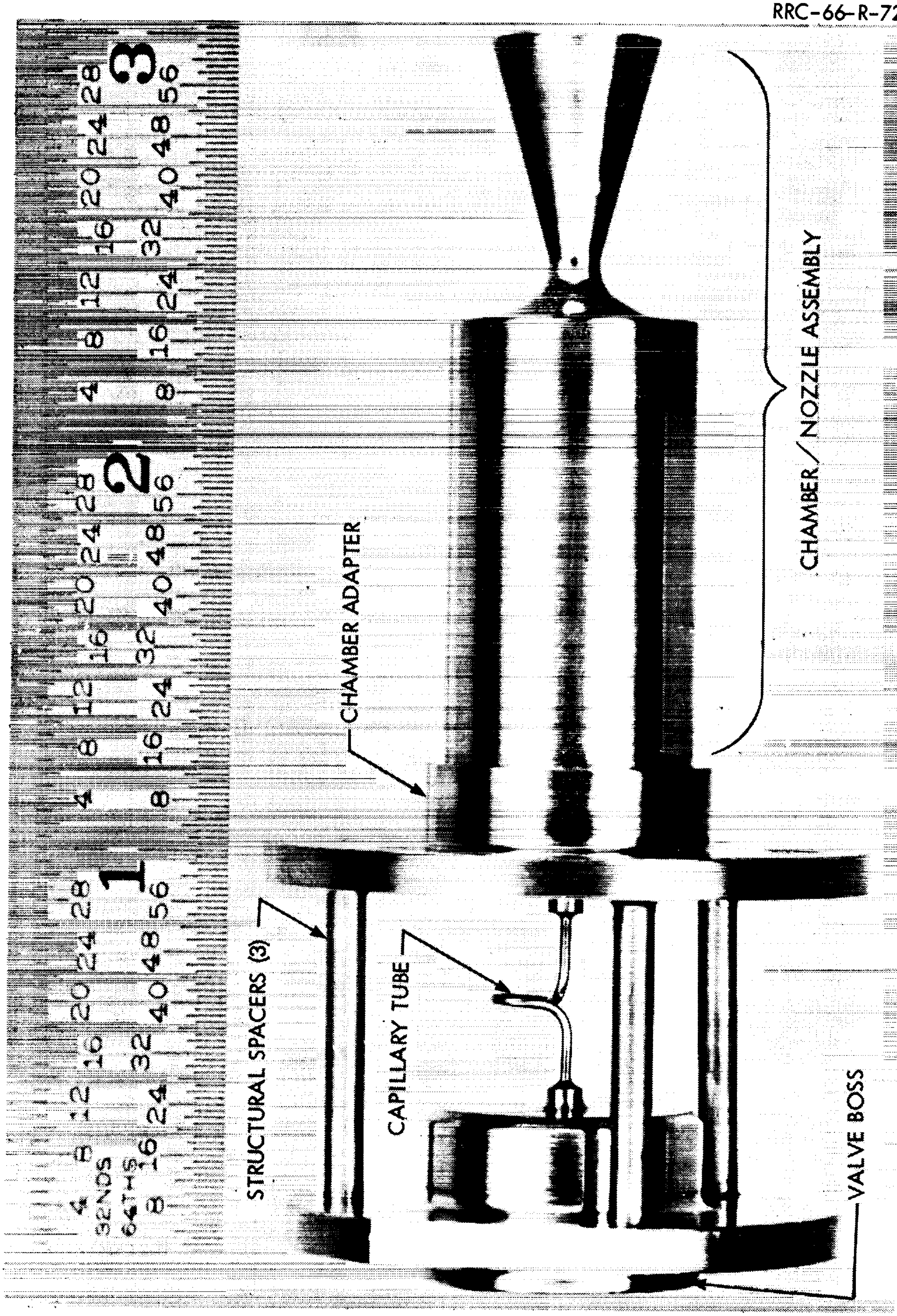


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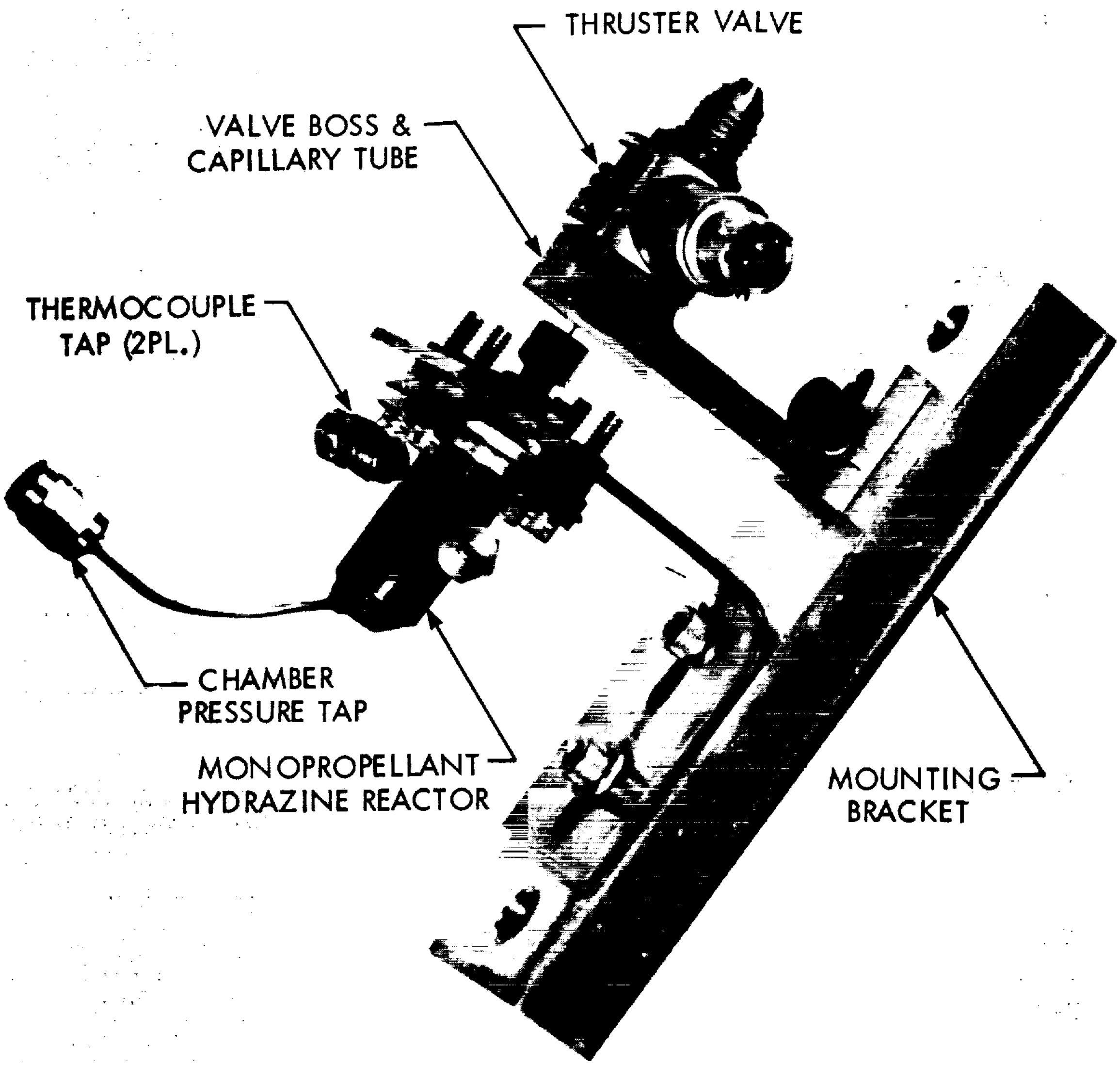
FIGURE 8

4.0 TESTING

4.1 Developmental Reactor

Initial injection system evaluation consisted of three (3) methods of injecting and distributing the propellant into the catalyst bed. These three (3) methods consisted of a capillary tube with woven wire mesh screens, sintered woven wire sheet, and electrolytic perforated plate. Figures 9, 10, and 11 depict the test setup for the developmental reactor tests. Figure 9 shows the reactor and valve on the mounting bracket. Figure 10 shows the propellant tank and pressurization feed system. Figure 11 shows the reactor, mounting bracket, and instrumentation prior to test. The first series of tests was conducted using a capillary tube and 200 mesh and 60 mesh woven wire cloth manufactured by Newark Wire Cloth Company, and located immediately downstream of the injection orifice. Test results obtained with this configuration indicated that this configuration was subject to roughness in chamber pressure (i.e., unstable flame front) and nonrepeatability of performance. Visual observation of the screens after test showed that the dynamic pressure of the propellant stream had parted the screen mesh and hydrazine was being injected directly into the catalyst bed without any stream breakup. Post-test observation of the catalyst bed indicated that without mechanical breakup and proper distribution of the injectant, local packing and coring of the catalyst bed occurs. Once a void is realized, it is difficult to establish a stable flame front which results in fluctuating chamber pressure. A typical oscillograph trace of chamber pressure and valve current for this injector configuration under warm bed conditions showed an ignition delay (from the start of valve open to start of chamber pressure rise) of approximately 7 milliseconds, a response time (from start of valve open to 90% of steady state chamber pressure) of approximately 60 milliseconds, and shutdown (valve start close to 10% of steady state chamber pressure) of approximately 200 milliseconds.

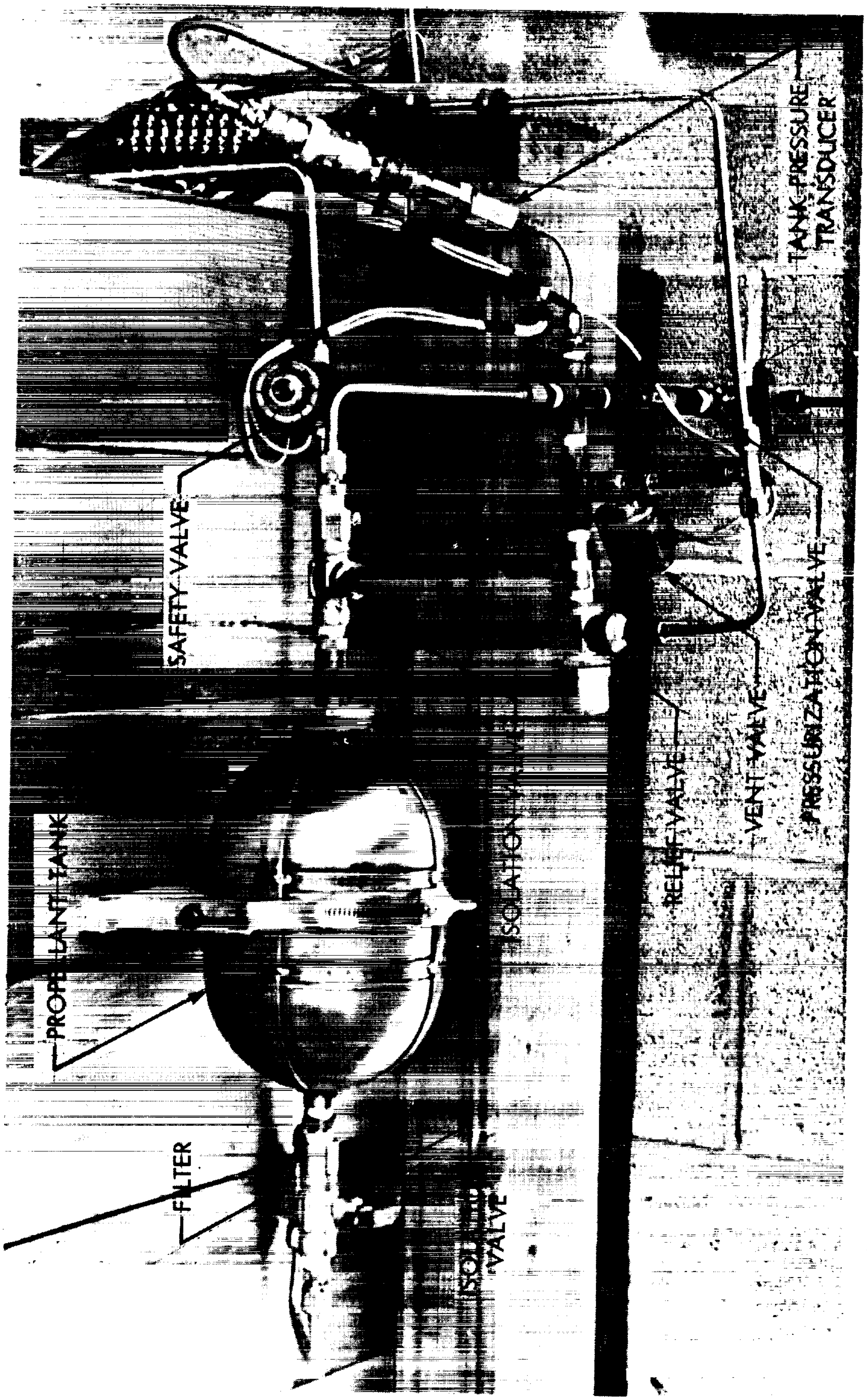


DEVELOPMENT SYSTEM

0.5 lbf THRUST REACTOR AND VALVE

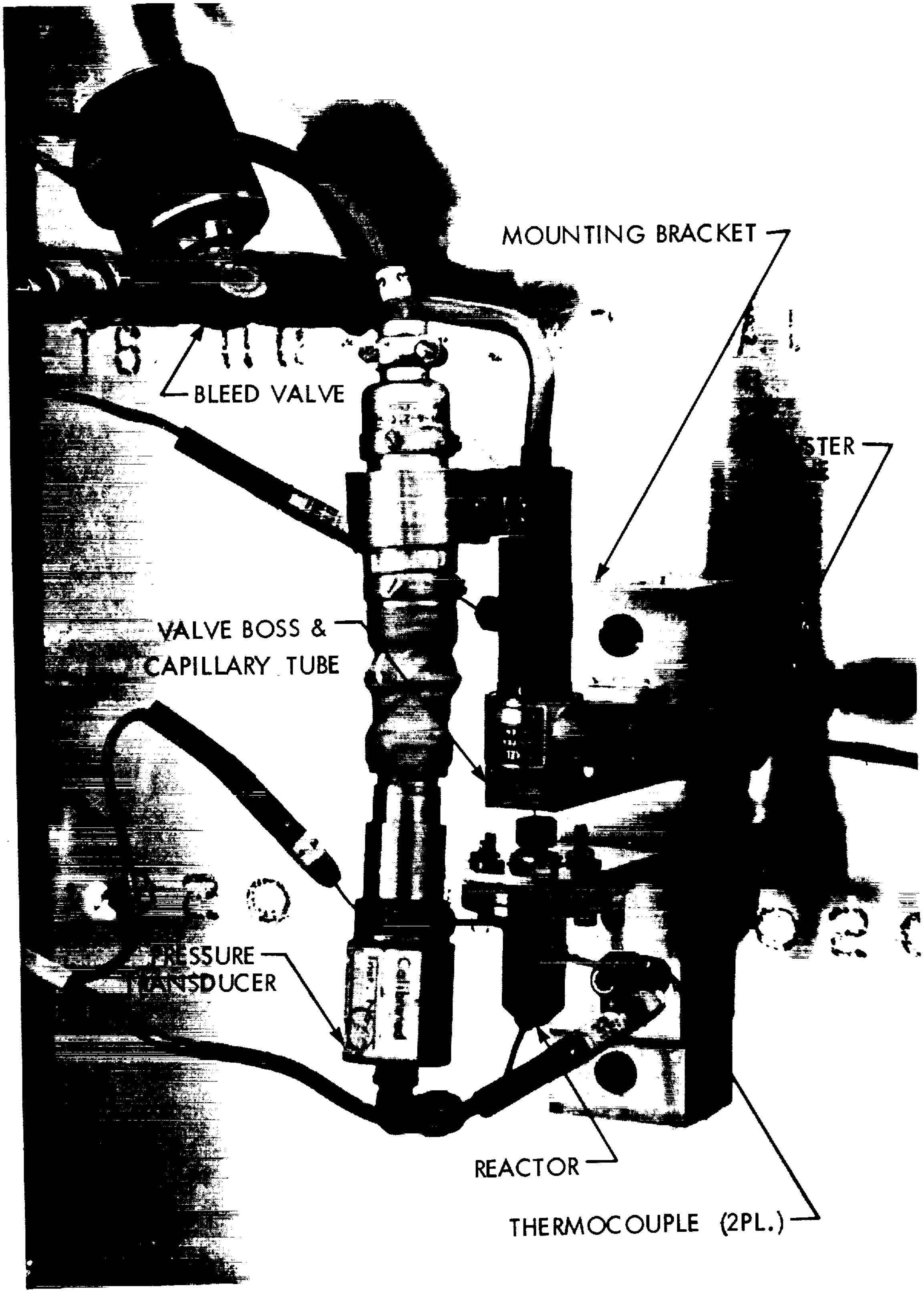
FIGURE 9

12093



DEVELOPMENT SYSTEM
PROPELLANT TANK AND FEED SYSTEM

FIGURE 10



DEVELOPMENT SYSTEM
0.5 lbf THRUST REACTOR AND INSTRUMENTATION

12100

FIGURE 11

The roughness in chamber pressure is reflected in chamber pressure fluctuations of approximately ± 6% of steady state run level chamber pressure. The next series of injection tests was conducted with a sintered woven wire sheet (trade name Rigimesh) produced by Aircraft Porous Media Incorporated. Although this injector produced less pressure fluctuations in chamber pressure, cold bed starts were accompanied by excessive ignition delays and excessive chamber pressure spikes. A typical chamber pressure spike with a cold bed start was on the order of 300 psia. Although chamber pressure fluctuations had decreased to ± 3.5% of steady state run level, response times for both hot bed and cold bed starts were increased. Only one configuration of this injector was evaluated and it is felt that with a properly designed manifold and an adequate pressure drop across the injector, that performance could be greatly improved.

The next series of tests was designed to evaluate electrolytic perforated plate manufactured by the Pyramid Screen Company. The plate area was about one-fourth the area of the catalyst bed and was fed by a manifold .010 of an inch deep and covering approximately 80% of the plate area. Various plates were used during this evaluation and included variations of percent open area, variations of hole diameter, and variations of plate thickness. Tests were conducted to evaluate two (2) injection systems consisting of a capillary tube, a manifold, and an electrolytic perforated plate. The manifold which was fed by a capillary tube was .010 of an inch deep and 0.200 of an inch in diameter. The first plate to be evaluated had orifice diameters of .0067 inches with a percent open area of 14.5%. The second plate had orifice diameters of .0051 inches and an 8% open area. Typical hot bed performance for the injector plate with the .0067 inch orifice and the 14.5% open area was 80 milliseconds response from propellant valve start open to 90% of nominal steady state chamber pressure, and 240 milliseconds from propellant valve start closed to 10% of steady state chamber pressure, and chamber pressure fluctuations of ± 2% nominal steady state nominals. Typical hot bed performance for the injector plate with the

.0051 inch orifices and 8% open area was 60 milliseconds response from valve start open to 90% of nominal steady state chamber pressure, 100 milliseconds response from valve closed to 10% of nominal steady state chamber pressure, and chamber pressure fluctuations of ± 2% of steady state values. After approximately 10 tests, it was planned to run the reactor continuously for 6 minutes which is equivalent to a 175 lbf-sec mission. During these tests it was found that if the reactor was run longer than approximately 60 seconds, chamber pressure fluctuations would increase until chamber pressure excursions were of a magnitude capable of rupturing the main flange gasket. Post-test analyses showed that with the manifold being used, propellant holdup was excessive with areas of flow stagnation which resulted in local detonation in the manifold cavity.

The injector plate manifold was redesigned using a reduced propellant manifold of .050 inches in diameter and .01 inches deep. A perforated plate with a .0051 inch diameter orifices and a 3 1/2% open area was evaluated with this redesigned manifold. Results from this injector were extremely encouraging in that hot bed performance of 60 milliseconds response from propellant valve start open to 90% of steady state chamber pressure, 200 milliseconds from propellant valve start close to 10% of steady state chamber pressure, and chamber pressure fluctuations of ± 1.8% of nominal steady state values were realized. More significantly, the reduced manifold volume appeared to have alleviated the problem associated with propellant boiloff or detonation behind the perforated injector plate. The reactor with the above mentioned injector configuration was successfully operated under a 50% and 100% duty cycle for an accumulated burn time of 3 minutes.

On the basis of the above described injector evaluation tests, it was decided to modify the injection system to use an orifice plate. This injection system consisted of a capillary tube feeding a manifold which was .010 inches deep and .050 inches in diameter. Within the manifold, 5 orifices were contained with nominal diameters of .006 inches. During the first test with this injector configuration, propellant flowed up around the conax fitting which was holding the capillary tube, became stagnant, and, with time, detonated. After the first test with the orifice plate injection system, the conax fitting was modified so that the capillary tube was brazed at the outlet of the conax fitting restricting any flow up into the conax fitting. After modification of the conax fitting, a series of tests was conducted and injector design was finalized. During this last series of tests, chamber pressure fluctuations did not exceed $\pm$ 3.5% of nominal steady state chamber pressure and there were no random pressure excursions during any of these tests. Two of these tests were of a duration such that approximately .75 pounds of propellant was consumed. The .75 pounds of propellant consumption was chosen because the propellant tank bellows assembly in the end item hardware is capable of expelling approximately .75 pounds of hydrazine. Average hot bed ignition delays for this last series of tests had a typical value of 5 milliseconds with response time (from propellant valve start open to 90% of nominal steady state chamber pressure) of approximately 60 milliseconds, and tailoff (time from nominal steady state chamber pressure to 10% of nominal steady state chamber pressure) of approximately 100 milliseconds. All the tests conducted on the developmental reactor are summarized in Table III.

4.2 End Item Hardware

4.2.1 Components

All of the components which were used in the end item monopropellant hydrazine thruster system were acceptance and prequalification tested. The propellant shutoff valves which are a Model AF 77C-B41 coaxial solenoid valve manufactured by the Eckel Valve Company were acceptance and prequalification tested in accordance with RRC-TS-0012, Test Specification Acceptance and Qualification Test Hydrazine Propellant Solenoid Valve.

Test No.	Duty Cycle %	Pulse Width sec.	Reactor L* in.	Injector	P_T psia	P_c psi
01	100	30	120	Capillary tube & 200 mesh screen	282	63
02		30			284	29
03		30			288	87
04		20			292	87
05		30			291	117
06		30			272	15
07		35			272	87
08		30			261	111
09		30			315^{+}	129
10		30			240	15
11		30			240	15
12		30			241	26
13		16			238	165
14		13			232	161
15	100	8			232	160
16	random pulses	varied			232	163
17	"	"			192	139
18	"	"			190	139
19	100	9			402	149
20	random pulses	varied			400	155
21					271	115
22					243	113
23					193	91
24					280	122
25					245	111
26					294	105
27	random pulses	varied	120	Capillary tube & 200 mesh screen	292	103

TABLE III

ENGINE TEST DATA SUMMARY

T_{c-1} °F	T_{c-2} °F	w lbm/sec	c* ft/sec	Remarks
1503	1211	N.A.	N.A.	Capillary tube has 0.010 inch I.D.
1394	1189			
1503	1290			
1617	1291			
1613	1329			
275	273			
1303	1547			
208	1433			
285	1481			
1275	1010			Reactor shutdown immediately after start. Capillary tube has 0.014 inch I.D.
1061	323			Reactor shutdown immediately after start
1415	1205			
253	1658			
254	1655			
252	1655			
252	1658			
N.O.	N.O.			
N.O.	N.O.			
1426	1547			Capillary tube changed to 0.010 inch I.D.
1591	1636			
N.O.	N.O.			
1481	1534			
1329	1481			
1658	1437			
1394	251			
1492	N.O.			
1547	1437	N.A.	N.A.	

.5 lbf N_2H_4

Test No.	Duty Cycle %	Pulse Width sec.	Reactor L* in.	Injector	P_T psia	P_c psic
28	random pulses	varied	120	Capillary tube & 200 mesh screen	305	145
29	random pulses	varied	120		300	166
30	random pulses	varied	120		299	165
31	100	30	80		264	123
32	100	12	80		279	151
33	100	31	80		279	149
34	100	30	80		297	152
35	100	30	80		294	151
36	random pulses	varied	80		267	150
37	random pulses	varied	120	Capillary tube & rigimesh	267	146
38	100	15	80	Capillary tube & 200 mesh screen	279	97
39	random pulses	varied	80		279	117
40			120		285	41
41			120		283	145
42			120		283	142
43	random pulses	varied	80	Capillary tube & 200 & 60 mesh screen	273	139
44	100 and 50	30 and .5	80	Capillary tube & 60 mesh moly screen	273	139
45	100 and 50	60 and .5	120	" "	282	158
46	100 and 50	30 and .5	120	" "	282	158
47	100 and 50	30 and .5	120	Capillary tube - no screen	282	155
48	100	6 minutes	80	Capillary tube - 60 & 200 mesh screen	274	128
49	100	6 minutes	80	" "	275	115
50	100	6 minutes	80	" "	275	127
51	100	11 minutes	80	" "	275	125

T/
.5 lbf N_2H_4 EN

Test No.	Duty Cycle %	Pulse Width sec.	Reactor L* in.	Injector	P_T psia	P_c psia
52	100 and 50	30 and .5	80	Capillary tube & 60 P perforated plate	279	123
53	100 and 50	60 and .5	120	" "	273	154
54	100 and 50	45 and .5	↑	" "	273	152
55	100 and 50	30 and .5		" "	261	130
56	100 and 50	30 and .5		" "	300	157
57	100 and 50	30 and .5		Capillary tube & 60 R perforated plate	293	147
58	100 and 50	30 and .5		Capillary tube & 60 P perforated plate	282	138
59	100 and 50	30 and .5		" "	283	135
60	100 and 50	30 and .5		Capillary tube & 60 R perforated plate	282	115
61	100 and 50	30 and .5		" "	333	139
62	100 and 50	50 and .5		Capillary tube & 60 P perforated plate	256	98
63	100 and 50	30 and .5		" "	243	139
64	100 and 50	30 and .5	↓	" "	264	145
65	100 and 50	20 and .5	120	" "	263	119
66	V O	I D	V O	I D	V	O I
67	100 and 50	20 and .5	80	Capillary tube & 40 T perforated plate	261	79
68	100 and 50	20 and .5	80	" "	263	N.O.
69	100 and 50	20 and .5	120	" "	262	N.O.
70	100 and 50	20 and .5	↑	Capillary Tube	300	115
71	100 and 50	20 and .5		Capillary Tube	300	113
72	100 and 50	20 and .5	↓	Capillary tube & 50 R perforated plate	N.O.	165
73	100 and 50	20 and .5	120	" "	255	168

TABLE III (Cont'd)

ENGINE TEST DATA SUMMARY

T_{c-1} °F	T_{c-2} °F	w lbm/sec	c* ft/sec	Remarks
1646	1405	N.A.	N.A.	Capillary tube changed to 0.011 inch I.D.
1677	1455			
1676	1454			
1591	1448			
1613	1459			
1647	1503			Excessive chamber pressure fluctuations.
1675	1482			Excessive chamber pressure fluctuations.
1627	1483	N.A.	N.A.	Excessive chamber pressure fluctuations.
N.O.	N.O.	.00178	5100	Excessive chamber pressure fluctuations.
1547	862	N.A.	N.A.	Injector consisted of capillary tube and rigimesh. Starts were accompanied by large chamber pressure spikes.
1446	928	N.A.	N.A.	Chamber leaking around gasket.
1463	N.O.	.0021	4050	Chamber leaking around gasket.
N.O.	N.O.	.0029	N.A.	Chamber leaking around gasket.
1547	N.O.	.00287	3110	
1636	N.O.	N.A.	N.A.	
1669	N.O.	.0031	3260	
1669	N.W.	.0030	3360	Rough run. Chamber pressure fluctuation 15% P-P w/large pressure excursions.
1657	1483	.0027	3600	Amplifier gain wrong - no oscillograph record.
1580	1503			
1636	1459	.00261	3660	P_c fluctuation 13.5% P-P
1703	1372	.0021	4440	P_c fluctuation 12.5% P-P
1699	1426	.00213	3935	P_c fluctuation 12 - 13% P-P.
1658	1459	N.A.	N.A.	P_c fluctuation 13% P-P.
1658	1476	N.A.	N.A.	P_c fluctuation 15 - 18% P-P. Some pressure escursions.

GINE TEST DATA SUMMARY

T_{c-1} °F	T_{c-2} °F	w lbm/sec	c* ft/sec	Remarks
1658	1547	N.A.	N.A.	Injector manifold .250 inch diameter and .010 inches deep.
1580	1415			Rough run. Large pressure excursions. Blew main flange gasket.
1636	1396			Chamber pressure fluctuations 5.2% P-P. Roughness increased with pulses.
1481	1394			" " " " " " " " "
1514	1411			
1525	1415			P_c fluctuations 11% P-P.
1675	1411			P_c fluctuations 3.9% P-P.
1719	1404			P_c fluctuations 4% P-P. Roughness increased with pulsing.
1435	1349			P_c fluctuations 5.5% P-P. Roughness increased with pulses.
1536	1378			P_c fluctuations 5% P-P. Extreme roughness with pulsing.
1636	N.O.			P_c fluctuations 2.5% P-P. Run looked real good. Low chamber pressure.
N.O.	N.O.			P_c fluctuations 2.1% P-P. Good run.
1500	1496			P_c fluctuations 4.4% P-P. Roughness increased with pulsing.
1480	1437	N.A.	N.A.	P_c fluctuations 8% P-P. Roughness increases with pulsing.
D	V	O	I D	
1481	N.O.	N.A.	N.A.	Rough run. Low chamber pressure.
1547	1481			Rough run. Chamber pressure decreasing during run.
N.O.	N.O.			Large pressure excursions. Ruptured chambers.
1587	1407			P_c fluctuations 4.5% P-P. Roughness increased during pulsing.
1547	1470			Random pressure excursions.
1658	1448			Rough run. Random pressure excursions - increasing with pulsing.
1681	1492	N.A.	N.A.	P_c fluctuations 10% P-P. Extremely rough during pulsing. Blew main flange gasket.

.5 lbf N_2H_4

Test No.	Duty Cycle %	Pulse Width sec.	Reactor L* in.	Injector	P_T psia	P_c psia
74	100 and 50	20 and .5	120	Capillary tube & 50 R perforated plate	258	160
75	100 and 50	10 and .5	120	" "	269	172
76	100	60		Capillary tube and perforated plate		N C
77	100	65		Capillary tube & 40 R perforated plate		N C
78	random pulses	varied		" "	226	138
79	random pulses	varied		" "	225	138
80	100 and 50	varied		" "	222	100
81	100 and 50	varied		" "	217	129
82	100 and 50	varied		" "	245	151
83	random pulses	varied		Capillary tube & 40 T perforated plate	262	165
84	100 and 50	30 and 0.5		" "	246	145
85	100 & random pulses	30 & varied		" "	230	
86	random pulses	varied		" "	225	130
87	V O	I D		V O I	D	
88	random pulses	varied		Capillary tube and orifice plate	235	130
89a	100	30		" "	213	114
89b	varied	varied		" "	213	116 av
89c	100	32		" "	212	115
90a	100	42		" "	141	85
90b	50	.080		" "	141	85 av
91	100	36		" "	220	118
92a	100	29		" "	218	119
92b	50	.500		" "	218	119 av
93	100	300		" "	208.5	137.
94	50	.500		" "	202	135 av
95	100	300	120	" "	247	155

TABLE III (Cont'd)

ENGINE TEST DATA SUMMARY

	T_{c-1} °F	T_{c-2} °F	w lbm/sec	c* ft/sec	Remarks
	1625	1476	N.A.	N.A.	P_c fluctuations 3.5% P-P.
	1587	N.O.	N.A.	N.A.	Rough run. P_c fluctuations mixed with random pressure excursions.
)	DATA				Capillary tube plugged.
)	DATA				Capillary tube plugged.
	N.A.	N.A.	N.A.	N.A.	P_c fluctuations 4% P-P average - increasing with time.
	↑	↑	↑	↑	P_c fluctuations 4% P-P average - increasing with time.
					P_c fluctuations 6% P-P. Moderate P_c excursions.
					Random pressure excursions.
	↓	↓	↓	↓	Smooth start - P_c fluctuations became large after 5 seconds and during pulse mode operation.
	N.A.	N.A.	N.A.	N.A.	Unsteady P_c - Large random P_c excursions.
	V	O I	D		
	N.A.	N.A.	N.A.	N.A.	Good run - Detonation upon shutdown because of poor manifold design (propellant hold-up).
e.	↑	↑	↑	↑	
e.					
e.					
5					
e.	↓	↓	↓	↓	
	N.A.	N.A.	N.A.	N.A.	

Acceptance testing of the propellant valve consisted of proof testing, leak testing, electrical tests, and cycling tests which included 250 cycles with electrical and leak checks every 50 cycles. Prequalification tests which were conducted to determine the adequacy of the valve design consisted of initially acceptance testing, cycling tests, and endurance cycling tests. The cycling test included 5,000 cycles with electrical and leak tests every 1,000 cycles and the endurance tests included an additional 20,000 cycles with electrical and leak tests taken every 5,000 cycles.

The remaining components, propellant tank/bellows assembly, manual valves, pressurization and fill valves, propellant filter, and propellant feed lines were acceptance tested per RRC-TS-0013, Test Specification 0.5 lbf N_2H_4 Propulsion System, Contract No. NAS 5-9137. These tests consisted of leak and proof pressure checking.

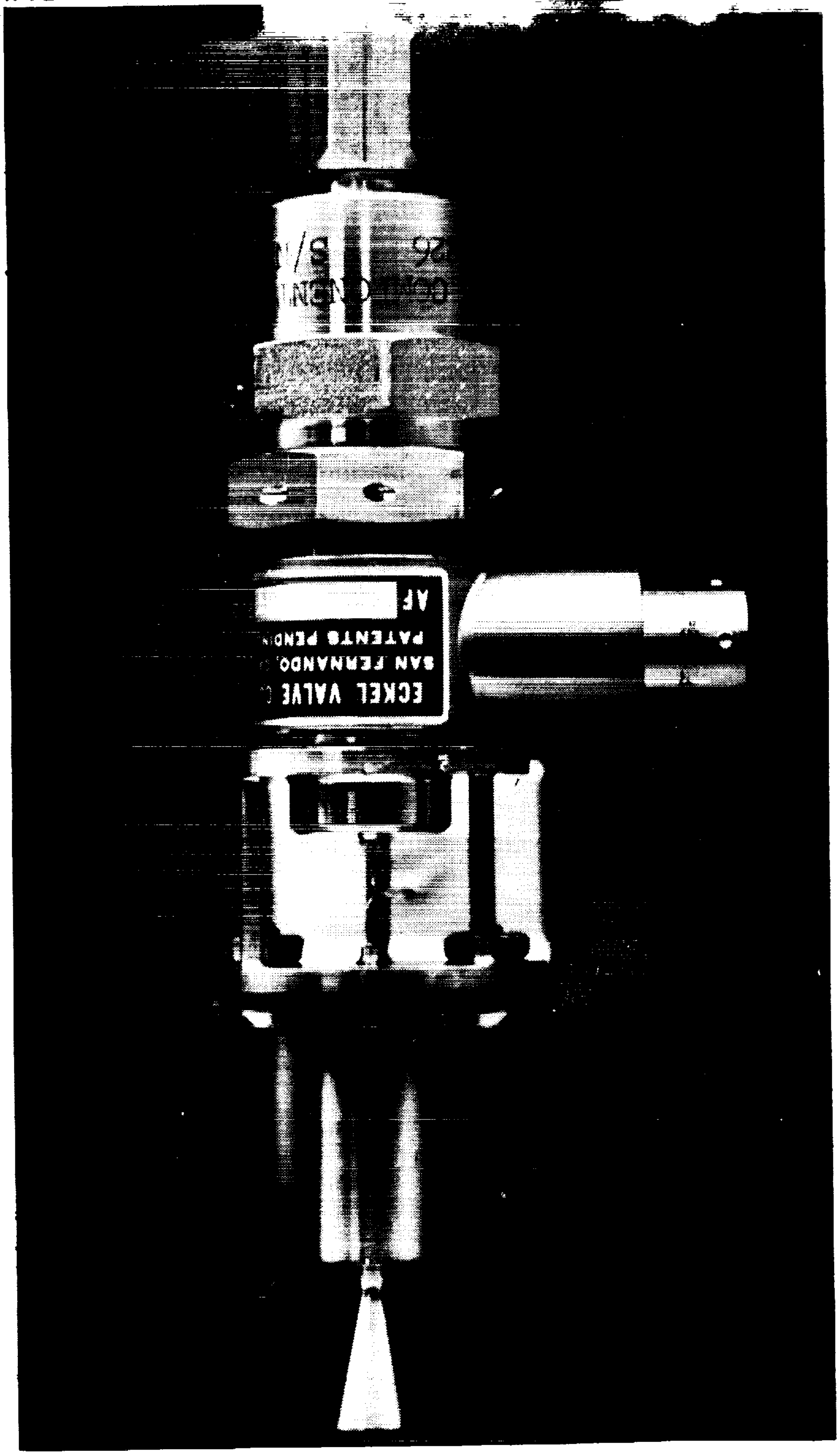
4.2.2 System Level

Prequalification of the end item monopropellant hydrazine reactor was accomplished at the system level. The test system included all items as delivered to Goddard Space Flight Center and consisted of a propellant tank/bellows assembly, manual shutoff valves, propellant fill and pressurization valves, propellant feed line, filter, propellant shutoff valve, and hydrazine reactor. All prequalification tests at the system level were conducted as the system was intended to be used. The system as depicted in Figures 12 and 13 was used in a blowdown gas pressure mode. Propellant filling and system pressurization was accomplished in accordance with procedures and test specifications recommended for lab test use (RRC-OP-0004).

4.2.3 Monopropellant Hydrazine Reactor

4.2.3.1 Prequalification

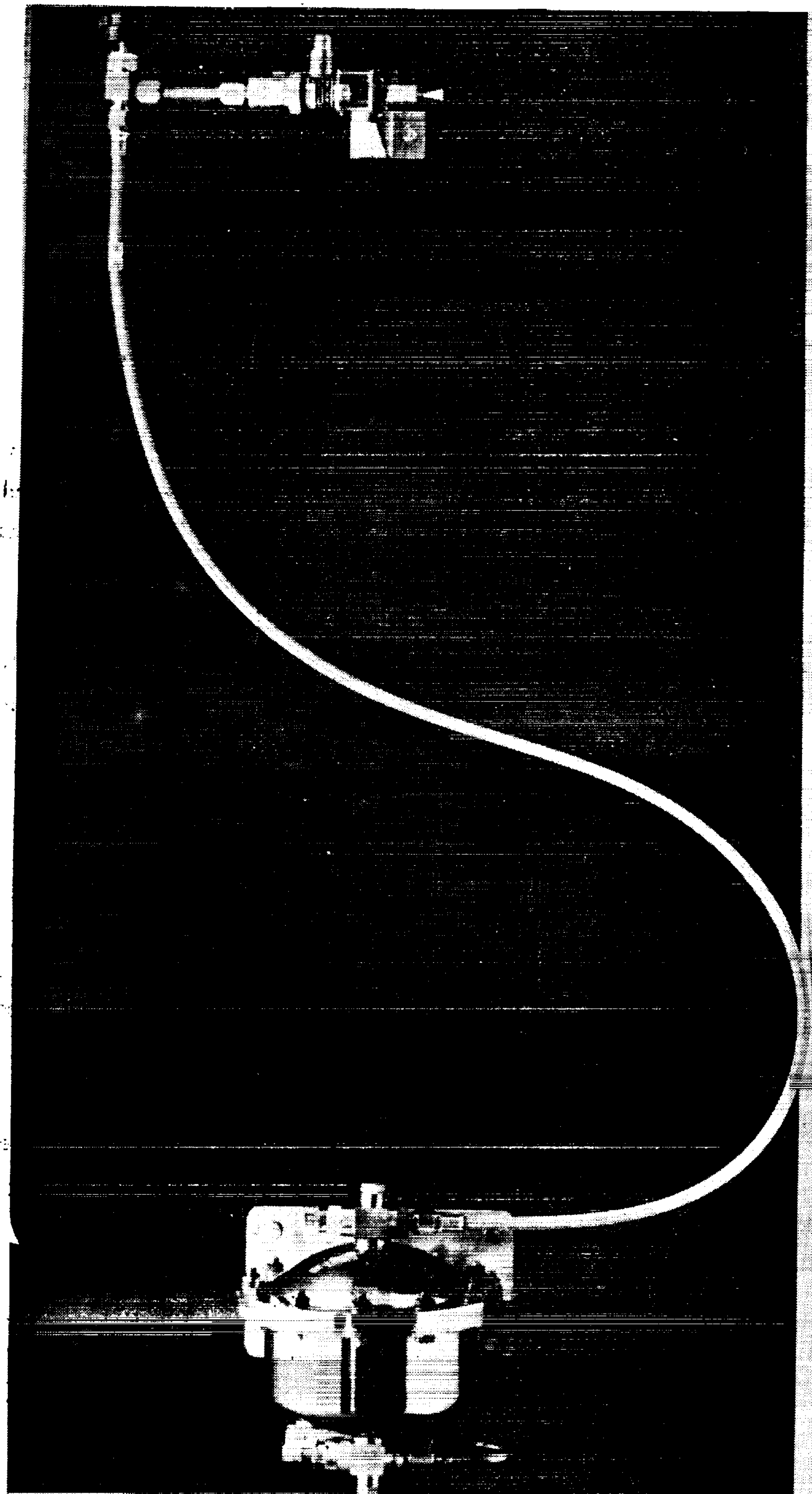
Prequalification testing of the hydrazine reactor was accomplished per RRC-TS-0013, Test Specification



END ITEM
HARDWARE PREQUALIFICATION TEST
0.5 lbf THRUST REACTOR

12095

FIGURE 12



END ITEM
HARDWARE PREQUALIFICATION TEST
0.5 lbf THRUST SYSTEM

12102

FIGURE 13

0.5 lbf N_2H_4 Propulsion System, Contract NAS 5-9137. Prequalification testing of the hydrazine reactor consisted of acceptance testing followed by successful completion of 5 static tests as summarized below.

a. A continuous firing for 5 minutes. Initial pressurization of the tank bellows assembly was 250 psig.

b. A firing at a duty cycle of 50% for 10 minutes with a pulse width of 500 milliseconds. Initial pressurization of the tank bellows assembly was 250 psig.

c. A firing with a duty cycle of 20% for 25 minutes with a pulse width of 300 milliseconds. Initial pressurization of the tank bellows assembly was 250 psig.

d. A continuous firing for 5 minutes. Initial pressurization of the tank bellows assembly was 250 psig.

e. A firing with a duty cycle of 50% for 10 minutes with a pulse width of 500 milliseconds. Initial pressurization of the tank bellows assembly was 250 psig.

Figure 14 shows a typical oscillograph trace from test (b.) above. This test was a 50% duty cycle with a pulse width of 500 milliseconds for approximately 600 cycles. Typical response and tailoff times were 32 milliseconds and 69 milliseconds respectively. Ignition delay was 4 milliseconds and chamber pressure fluctuations were $\pm$ 2.25% of steady state chamber pressure. Figure 15 shows a typical oscillograph trace from test (c.) above. This test was a 20% duty cycle with a pulse width of 300 milliseconds for approximately 1,000 cycles. Typical response and tailoff times for this test were 28 milliseconds and 57 milliseconds respectively. Ignition delay was 43 milliseconds and chamber pressure fluctuations were ± 1.94% of steady state chamber pressure. Figure 16 shows the oscillograph trace from run (e.) above. This test was identical to (a.) with a 50% duty cycle, a pulse width of 500 milliseconds for approximately 600 cycles. Response time and tailoff time was 29 milliseconds and 58 milliseconds respectively. The ignition delay was 4 milliseconds and the chamber pressure fluctuations were 3.17% of steady state chamber pressure. Approximately 1,300 seconds of accumulated burn time at various duty cycles and pulse widths was established prior to pulse number 169 in Figure 16.

Pressure and temperature data taken from the reactor prequalification test sequence is shown in Figures 17 through 26. Table IV is the test data summary for the reactor prequalification and acceptance testing.

Figures 16 and 17 are pressure and temperature data from run number 171-28-02-Q4. This was a continuous run for approximately 285 seconds. Initial chamber pressure was 125 psia and final was 95 psia. The chamber skin temperatures were 800°F to 1,000°F and the injector head and propellant valve boss were 500°F and 65°F respectively. At shutdown the injector head temperature climbed to 700°F before starting to cool and the propellant valve boss peaked at 76°F and then started to cool.

Figures 18 and 19 are pressure and temperature data from run 171-28-02Q5. This was a 50% duty cycle run with a pulse width of 500 milliseconds. Approximately 590 cycles were completed before shutdown. As seen in Figure 18 the chamber pressure was decreasing rapidly even though shutdown was not until 590 cycles. This was due to propellant flow rate rapidly decreasing with each pulse because the bellows containing the propellant was near its nested position. The temperature history as seen in Figure 19 is similar to the previous run 171-28-02-Q4.

Figures 20 and 21 are pressure and temperature data from run number 171-28-02-Q6. This was a 20% duty cycle run with a pulse width of 300 milliseconds. Approximately 905 pulses were completed prior to shutdown. Initial chamber pressure was 143 psia and final chamber pressure was 70 psia. Temperature at this duty cycle and pulse width were slightly lower than the previous two runs.

Figures 22 and 23 are pressure and temperature data from run number 171-28-02-Q7. This was a 100% duty cycle run with a pulse width of approximately 280 seconds. Initial chamber pressure was 150 psia and final chamber pressure was 80 psia. The temperature data for this run, as seen in Figure 23, is similar to runs number 171-28-02-Q4 and 171-28-02-Q5.

Figures 24 and 25 are pressure and temperature data from run number 171-28-02-Q8. This was a 50% duty cycle run with a pulse width of 500 milliseconds. Initial chamber pressure was 150 psia and final chamber pressure was 67 psia at shutdown. The temperature data, as seen in Figure 25, is similar to runs 171-28-02-Q4, 171-28-02-Q5, and 171-28-02-Q7.

4.2.3.2 Acceptance

Acceptance testing of the hydrazine reactor consisted of acceptance testing the injector which included leak tests, proof tests, and water flow calibration tests, and one calibration firing. The calibration firing consisted of a 60 second steady state test followed immediately with 10 cycles at a 50% duty cycle and a pulse width of 500 milliseconds.

Figures 27 and 28 show typical oscillograph traces from the acceptance tests of the two (2) reactors delivered to Goddard Space Flight Center under this contract. As seen in Figure 16, typical response time and tailoff time is 38 milliseconds and 80 milliseconds respectively. Ignition delays are 3 milliseconds and chamber pressure fluctuations are ± 2.1% of nominal steady state chamber pressure. Figure 27 shows response and tailoff times of 33 milliseconds and 52 milliseconds respectively for reactor S/N 02. Ignition delay is 3 milliseconds and chamber pressure fluctuations are ± .65% of nominal steady state chamber pressure.

Reactors S/N 01 and S/N 02 met all requirements of RRC-TS-0013, Test Specification 0.5 lbf N_2H_4 Propulsion System (GSFC) Contract NAS 5-9137.

TEST RECORD RUN NO. 171-28-02-Q5

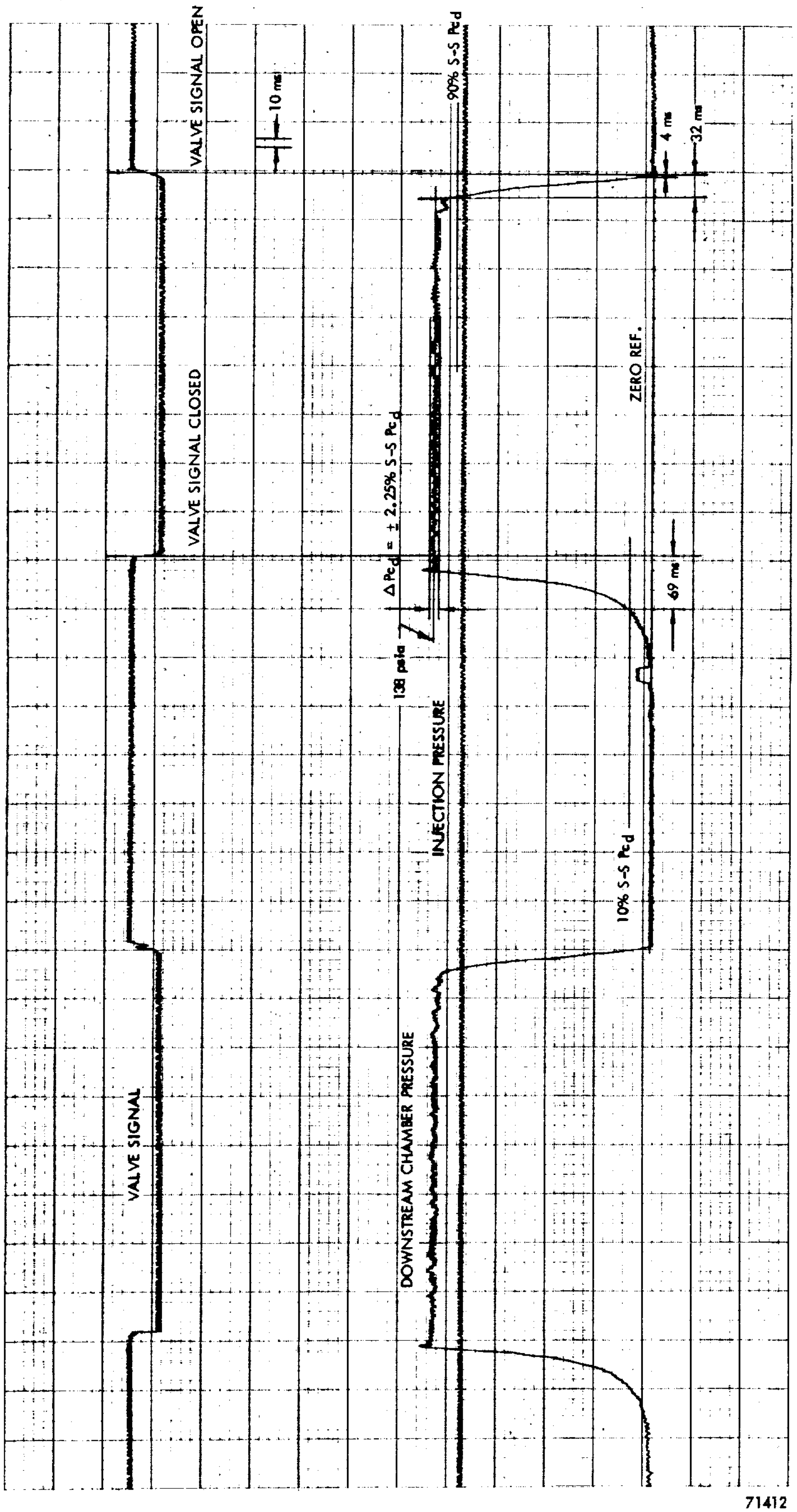
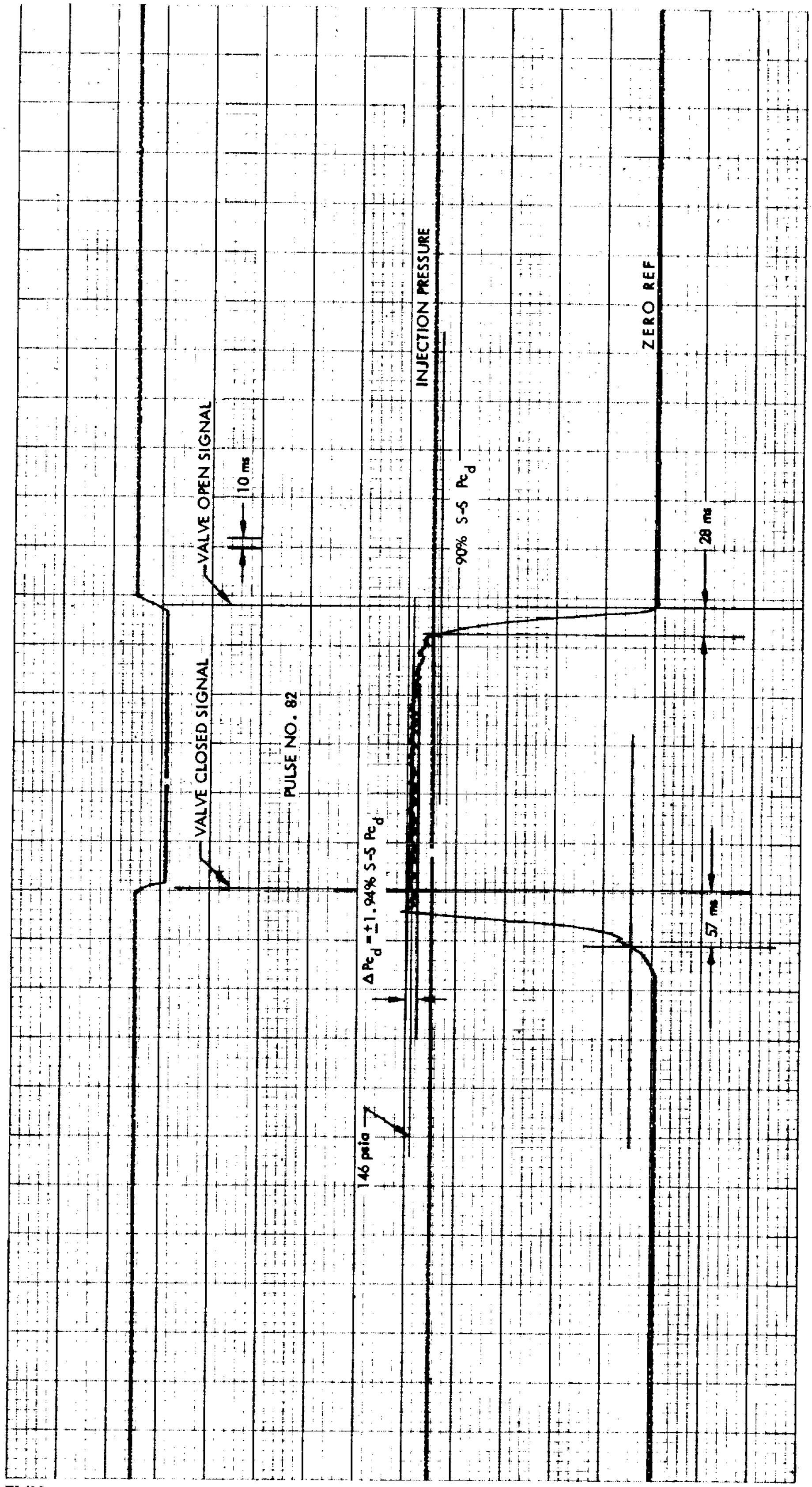


FIGURE 14

TEST RECORD RUN NO. 171-28-02-Q6



71413

FIGURE 15

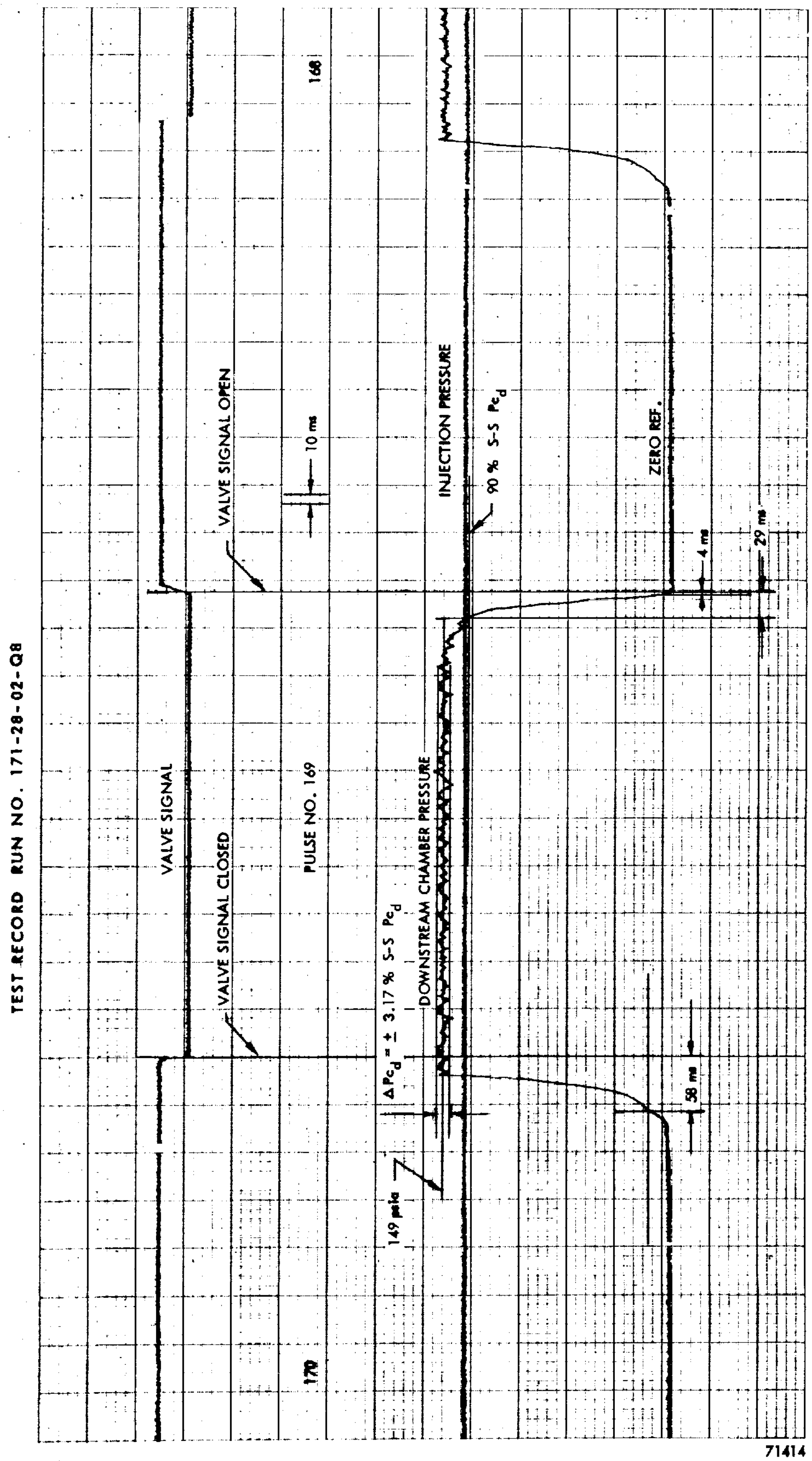
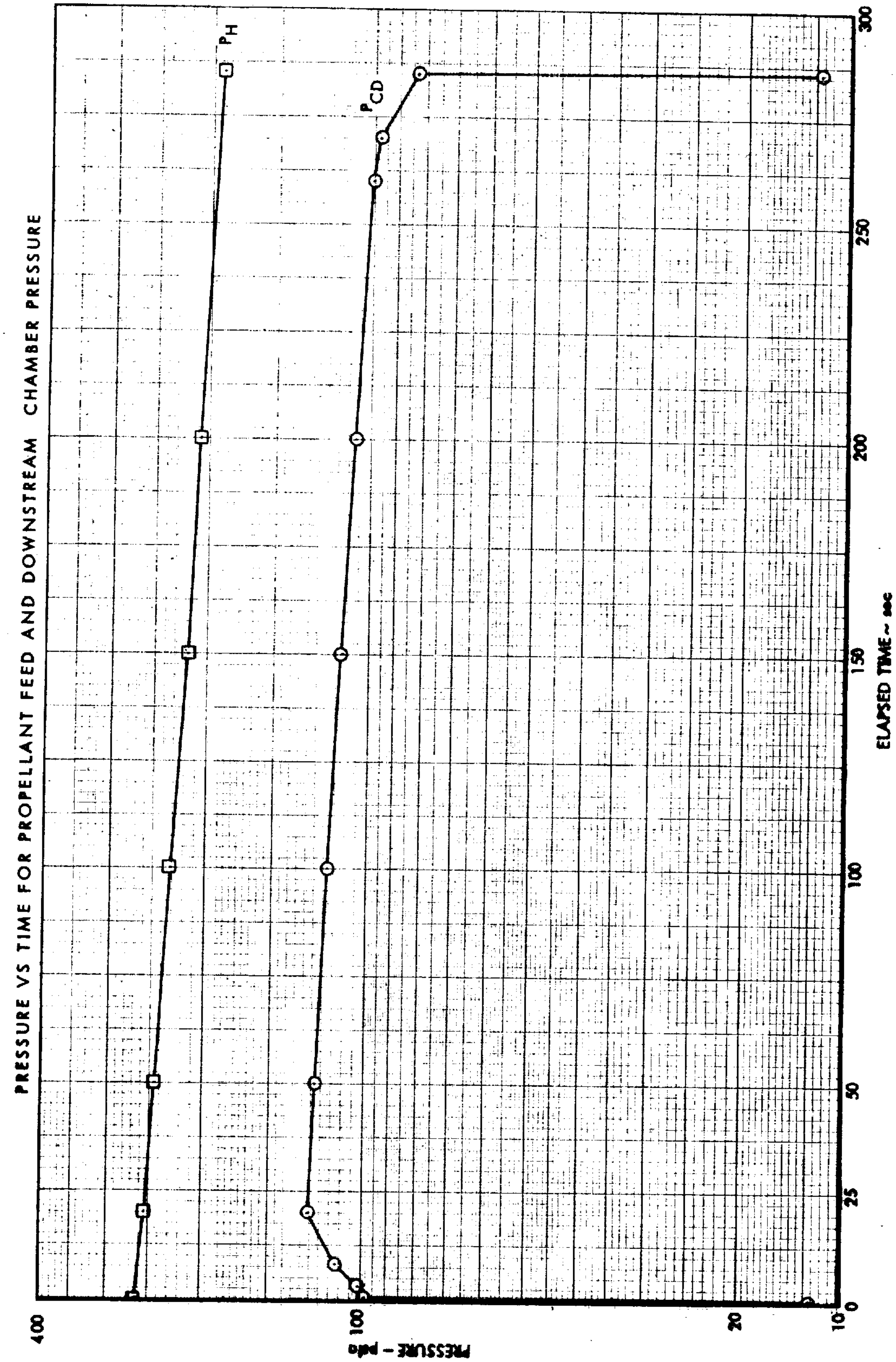

TEST RECORD RUN NO. 171-28-02-Q8
VALVE SIGNAL
VALVE SIGNAL OPEN
VALVE SIGNAL CLOSED
PULSE NO. 169
168
170
10 ms
INJECTION PRESSURE
90 % S-S Pc_d
DOWNSTREAM CHAMBER PRESSURE
$\Delta Pc_d = \pm 3.17$ % S-S Pc_d
149 psia
ZERO REF.
4 ms
29 ms
58 ms
71414

FIGURE 16



RUN NUMBER 171-28-02-Q4
NOVEMBER 10, 1965

71410

FIGURE 17

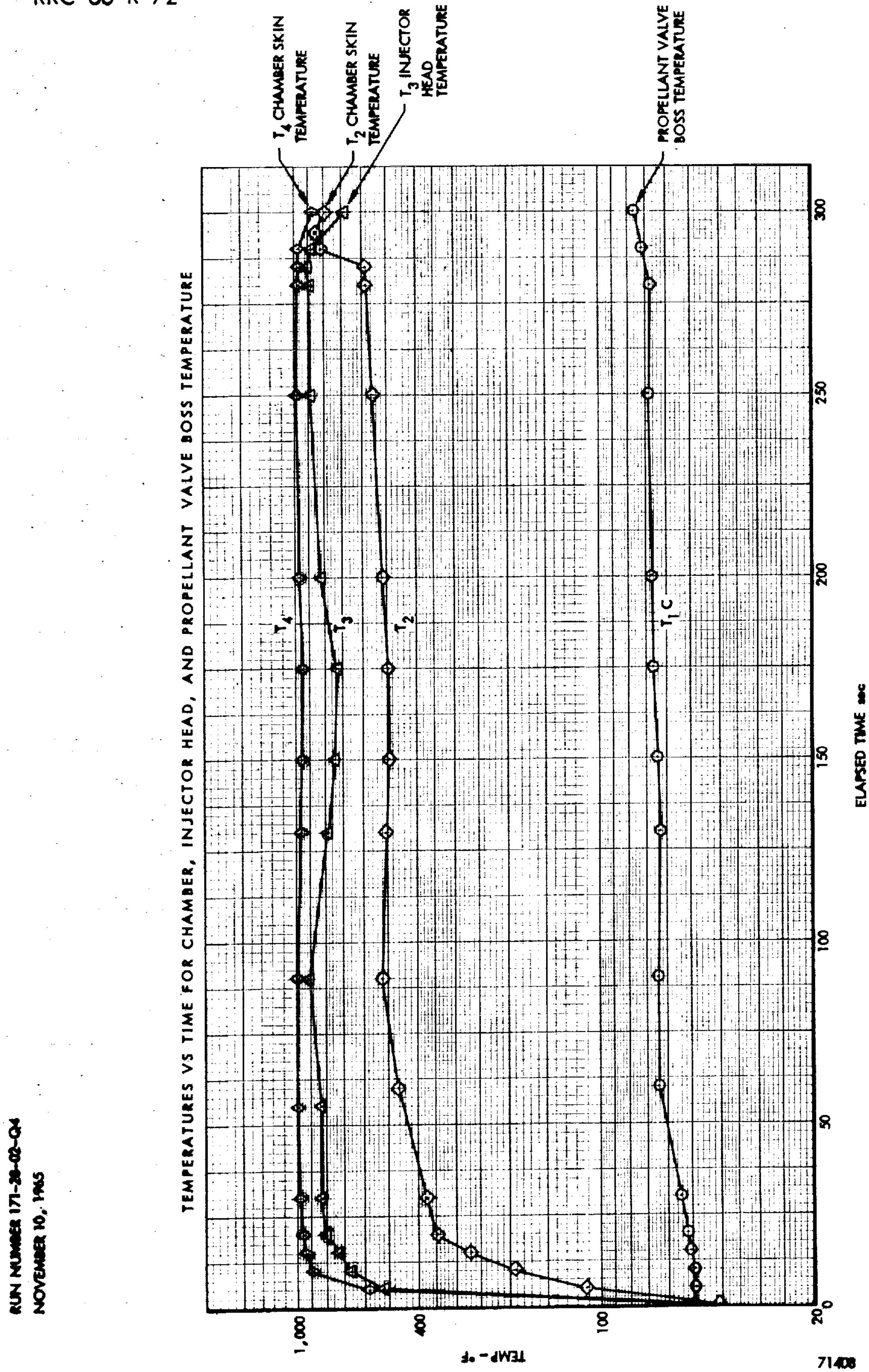
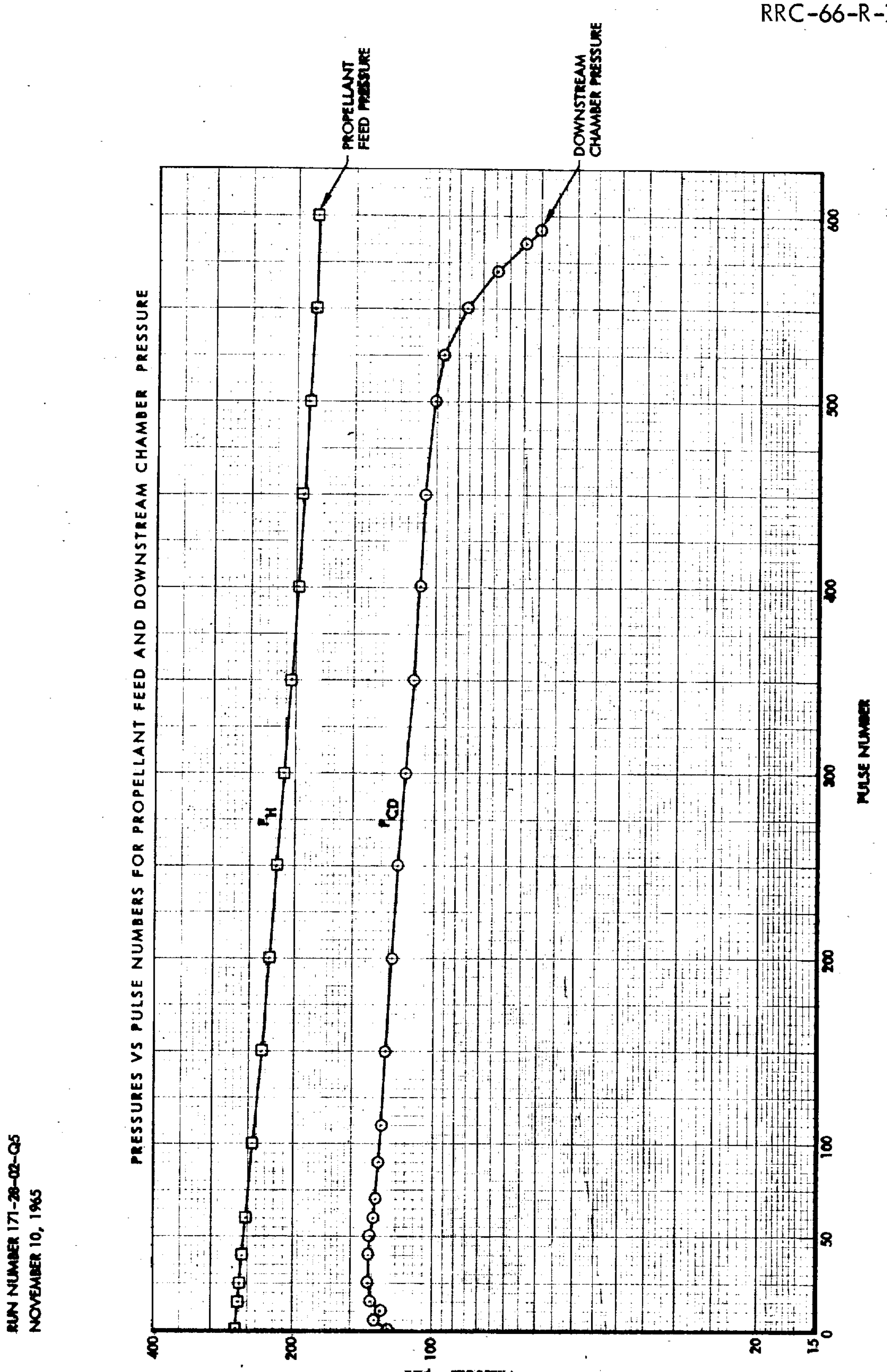

TEMPERATURES VS TIME FOR CHAMBER, INJECTOR HEAD, AND PROPELLANT VALVE BOSS TEMPERATURE
RUN NUMBER 171-28-02-Q4
NOVEMBER 10, 1965
T_4 CHAMBER SKIN TEMPERATURE
T_2 CHAMBER SKIN TEMPERATURE
T_3 INJECTOR HEAD TEMPERATURE
PROPELLANT VALVE BOSS TEMPERATURE
T_4
T_3
T_2
T_1C
TEMP - °F
1,000
400
100
20
ELAPSED TIME sec
0
50
100
150
200
250
300
71408

FIGURE 18



71405

FIGURE 19

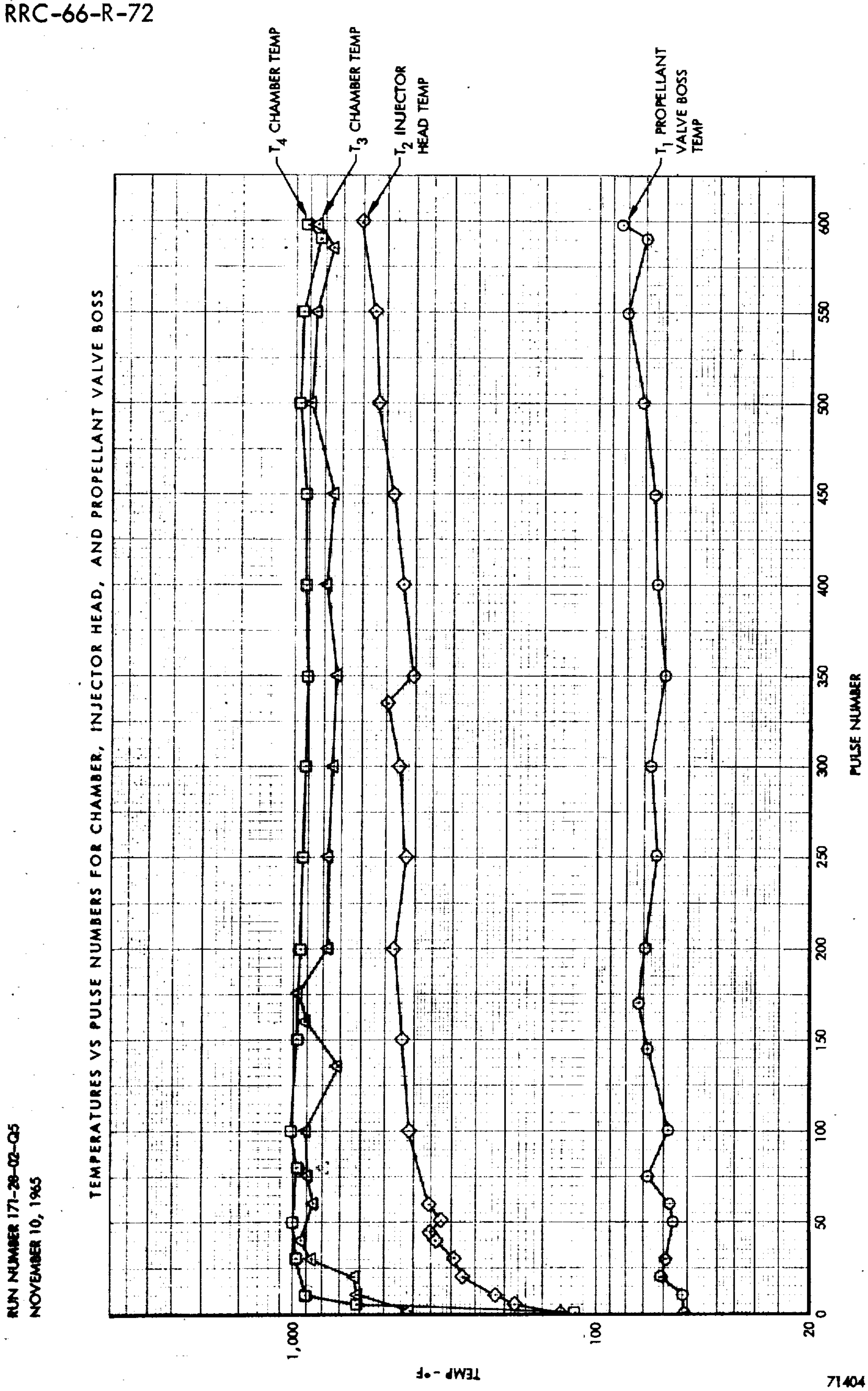
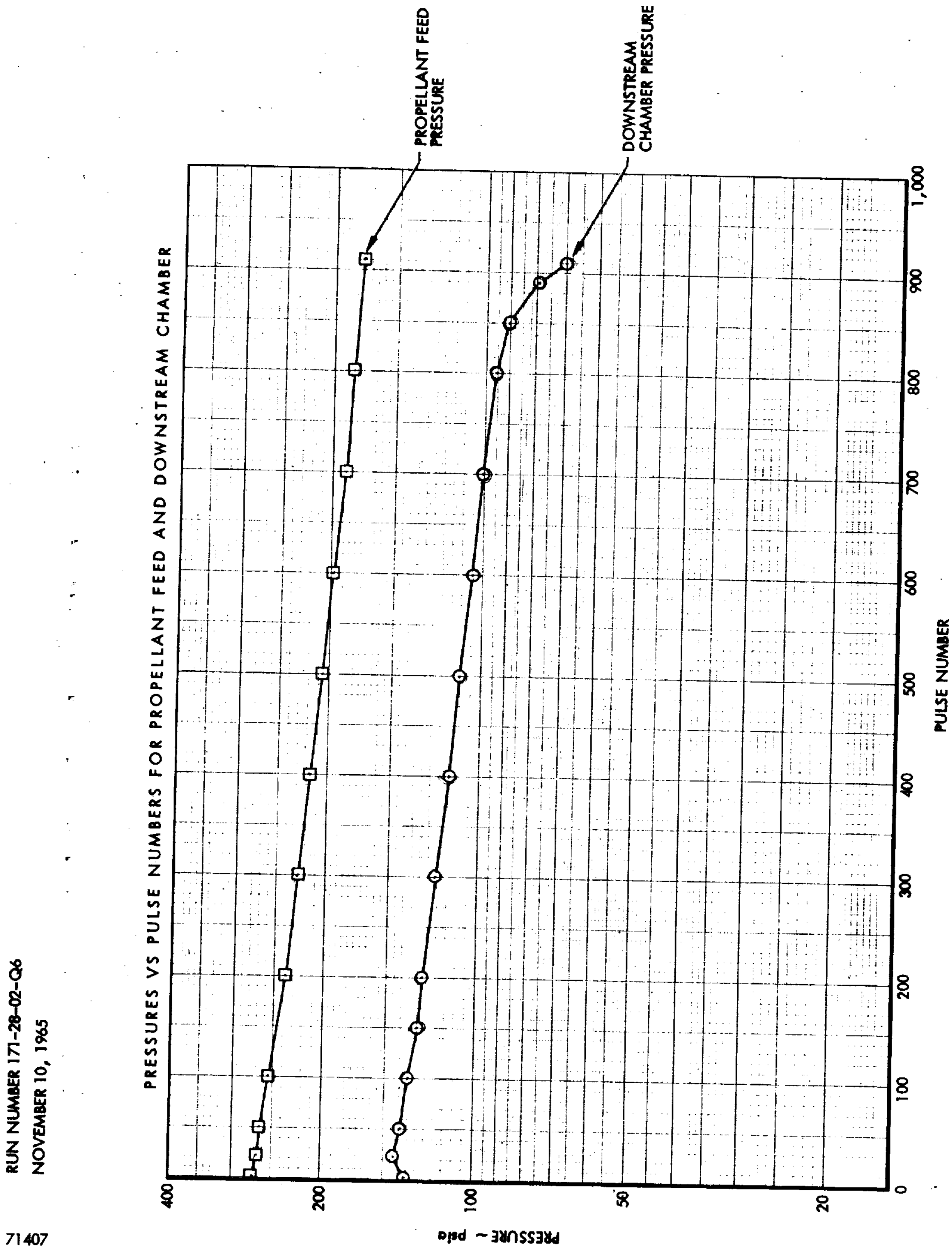

TEMPERATURES VS PULSE NUMBERS FOR CHAMBER, INJECTOR HEAD, AND PROPELLANT VALVE BOSS
RUN NUMBER 171-28-02-Q5
NOVEMBER 10, 1965
T_4 CHAMBER TEMP
T_3 CHAMBER TEMP
T_2 INJECTOR HEAD TEMP
T_1 PROPELLANT VALVE BOSS TEMP
1,000
100
20
TEMP - °F
0
50
100
150
200
250
300
350
400
450
500
550
600
PULSE NUMBER
71404

FIGURE 20



71407

FIGURE 21

RUN NUMBER 171-28-02-Q6 NOVEMBER 10, 1965

TEMPERATURES VS PULSE NUMBERS FOR CHAMBER, INJECTOR HEAD, AND PROPELLANT VALVE BOSS

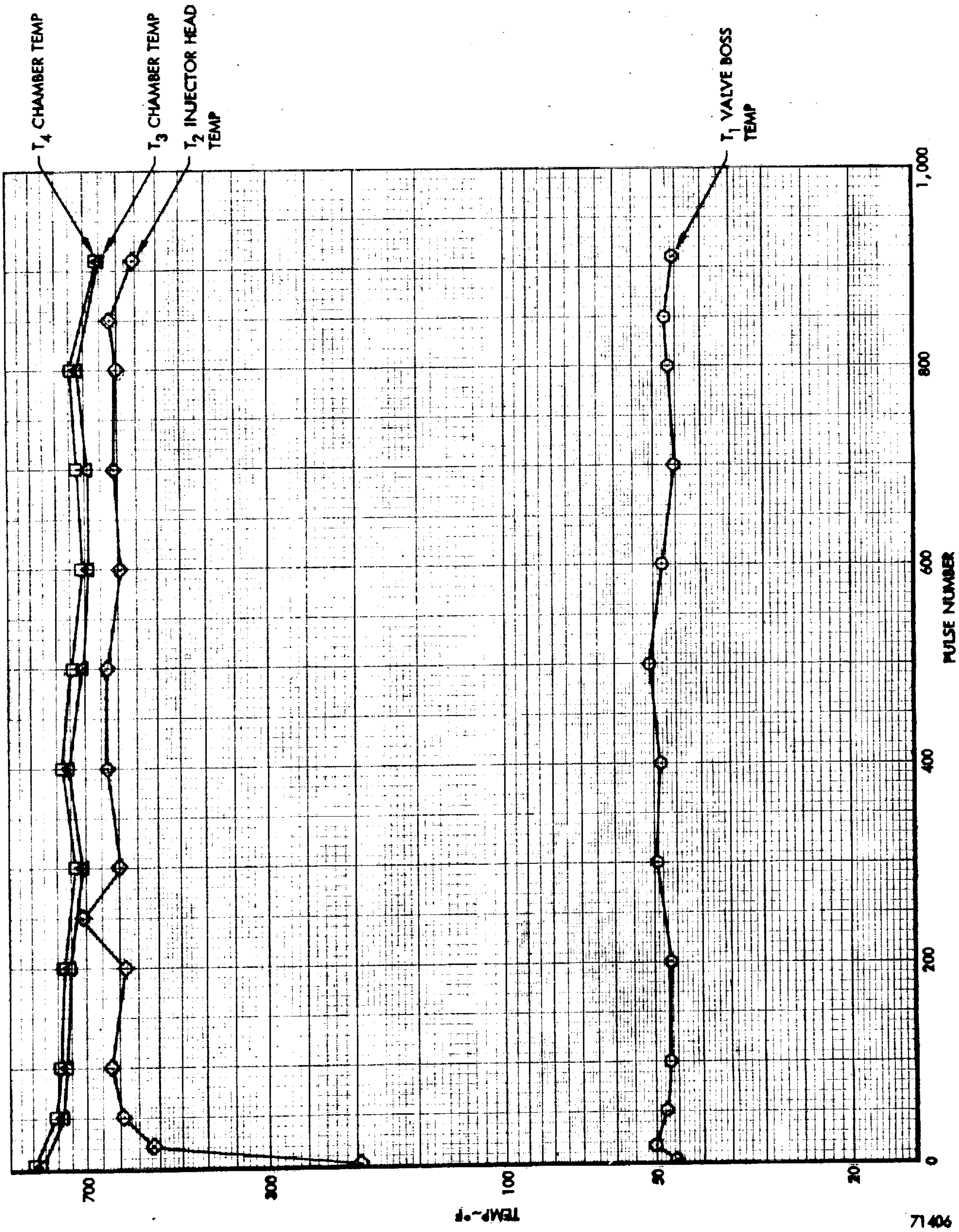
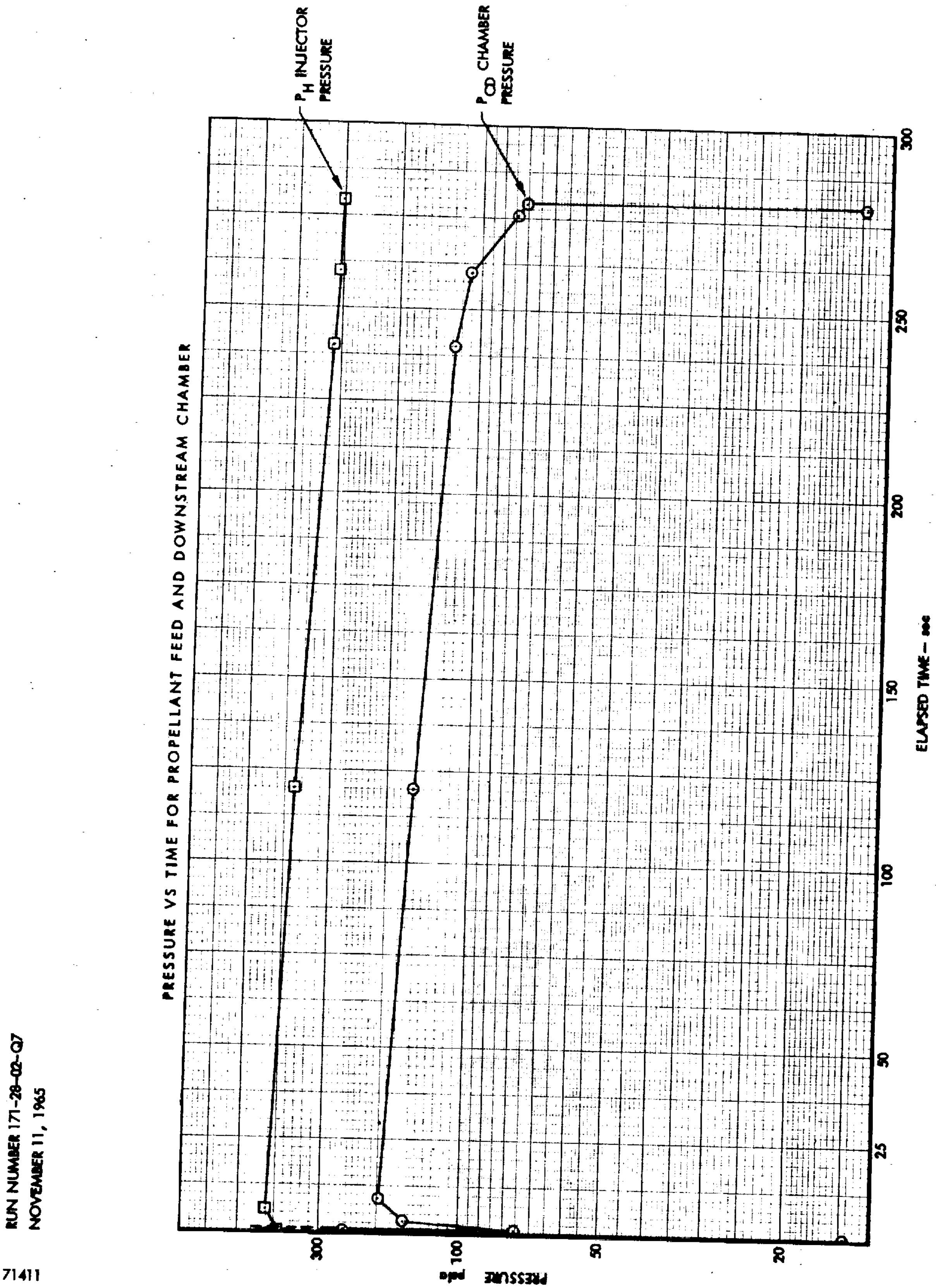


FIGURE 22



71411

FIGURE 23

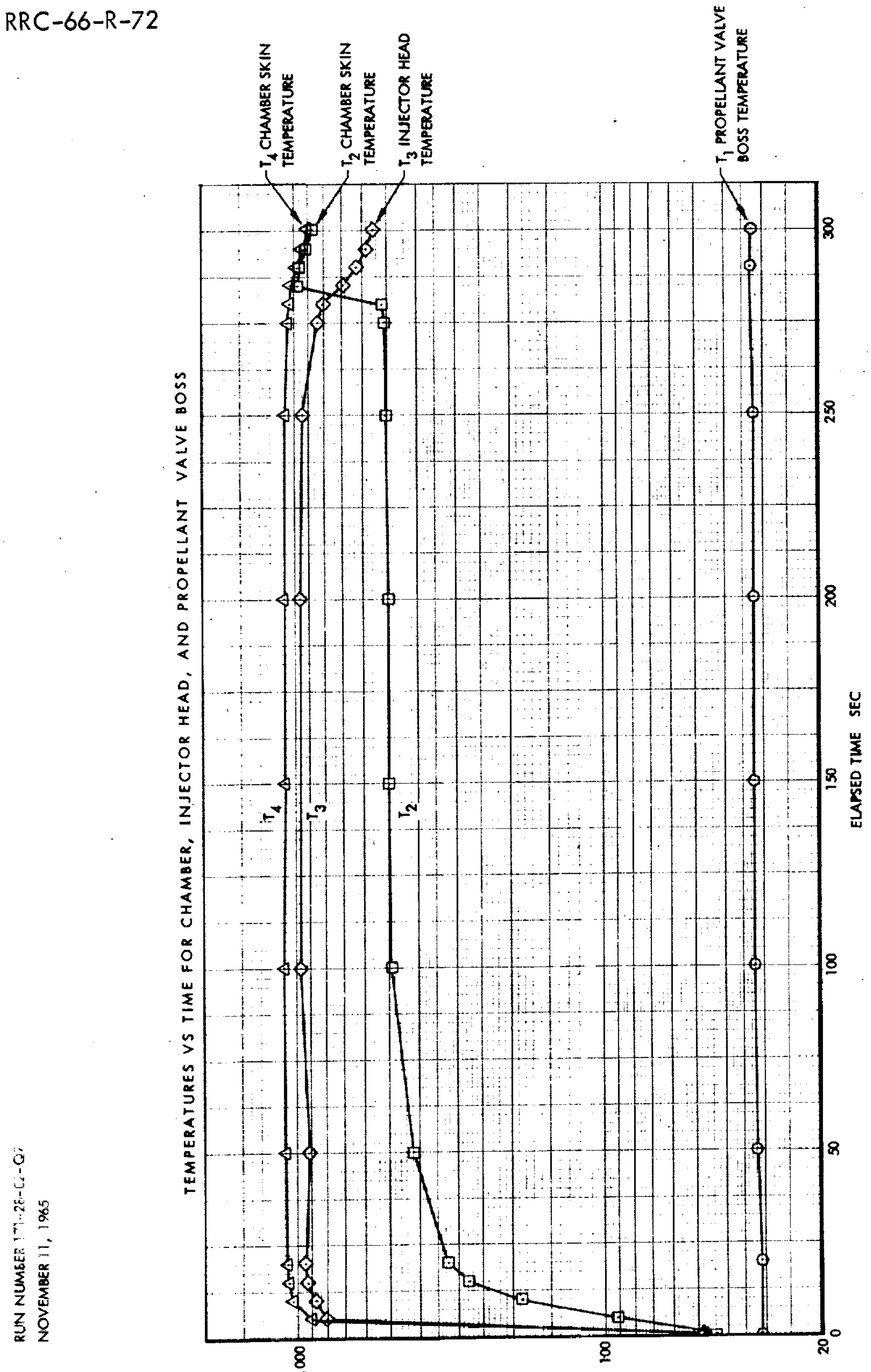

TEMPERATURES VS TIME FOR CHAMBER, INJECTOR HEAD, AND PROPELLANT VALVE BOSS
NOVEMBER 11, 1965
T4 CHAMBER SKIN TEMPERATURE
T2 CHAMBER SKIN TEMPERATURE
T3 INJECTOR HEAD TEMPERATURE
T1 PROPELLANT VALVE BOSS TEMPERATURE
T4
T3
T2
ELAPSED TIME SEC
0
50
100
150
200
250
300
TEMP °F
1,000
100
20
71409

FIGURE 24

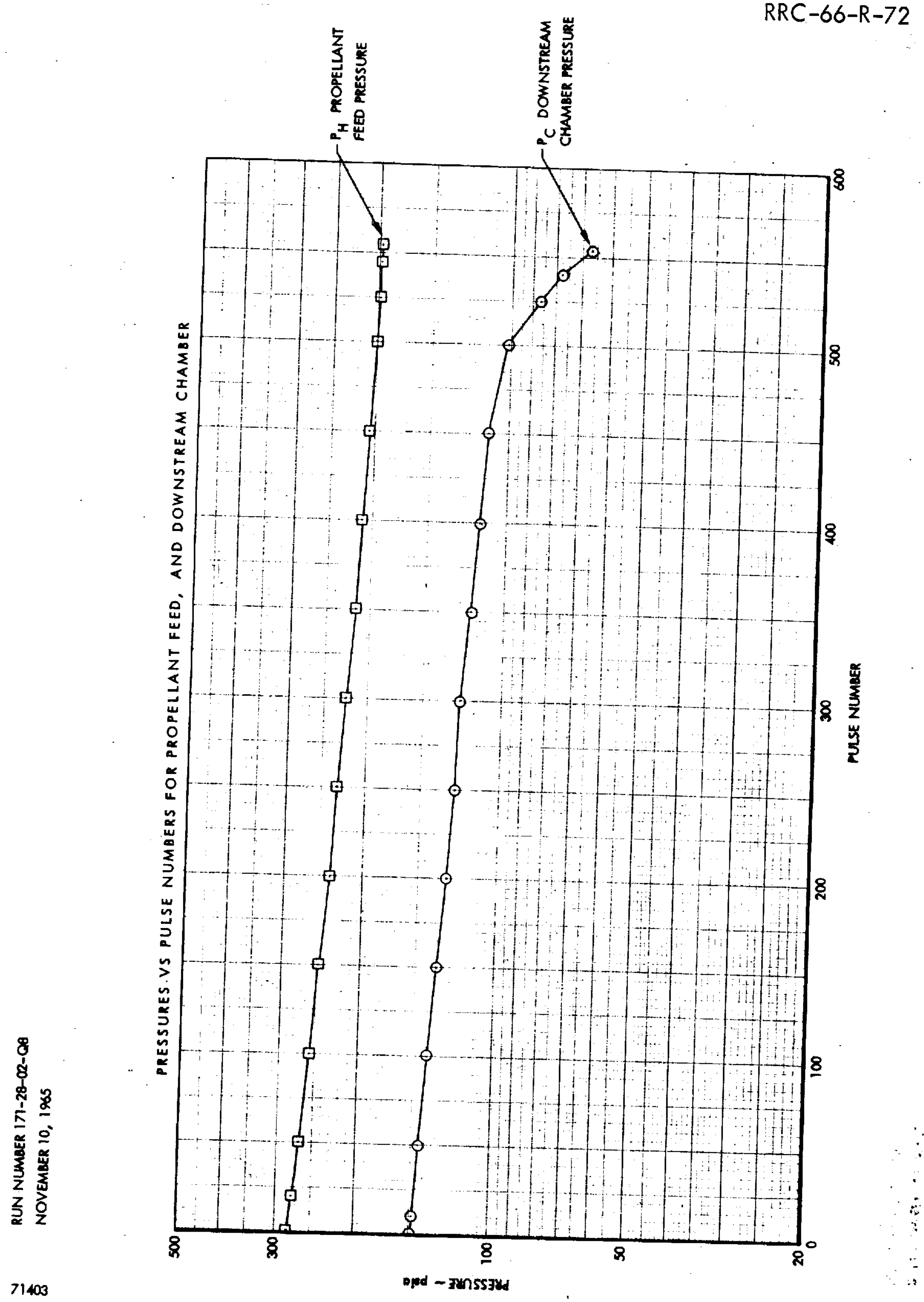

PRESSURES VS PULSE NUMBERS FOR PROPELLANT FEED, AND DOWNSTREAM CHAMBER
RUN NUMBER 171-28-02-Q8
NOVEMBER 10, 1965
P_H PROPELLANT FEED PRESSURE
P_C DOWNSTREAM CHAMBER PRESSURE
PRESSURE ~ psia
PULSE NUMBER
500
300
100
50
20
0
100
200
300
400
500
600
71403

FIGURE 25

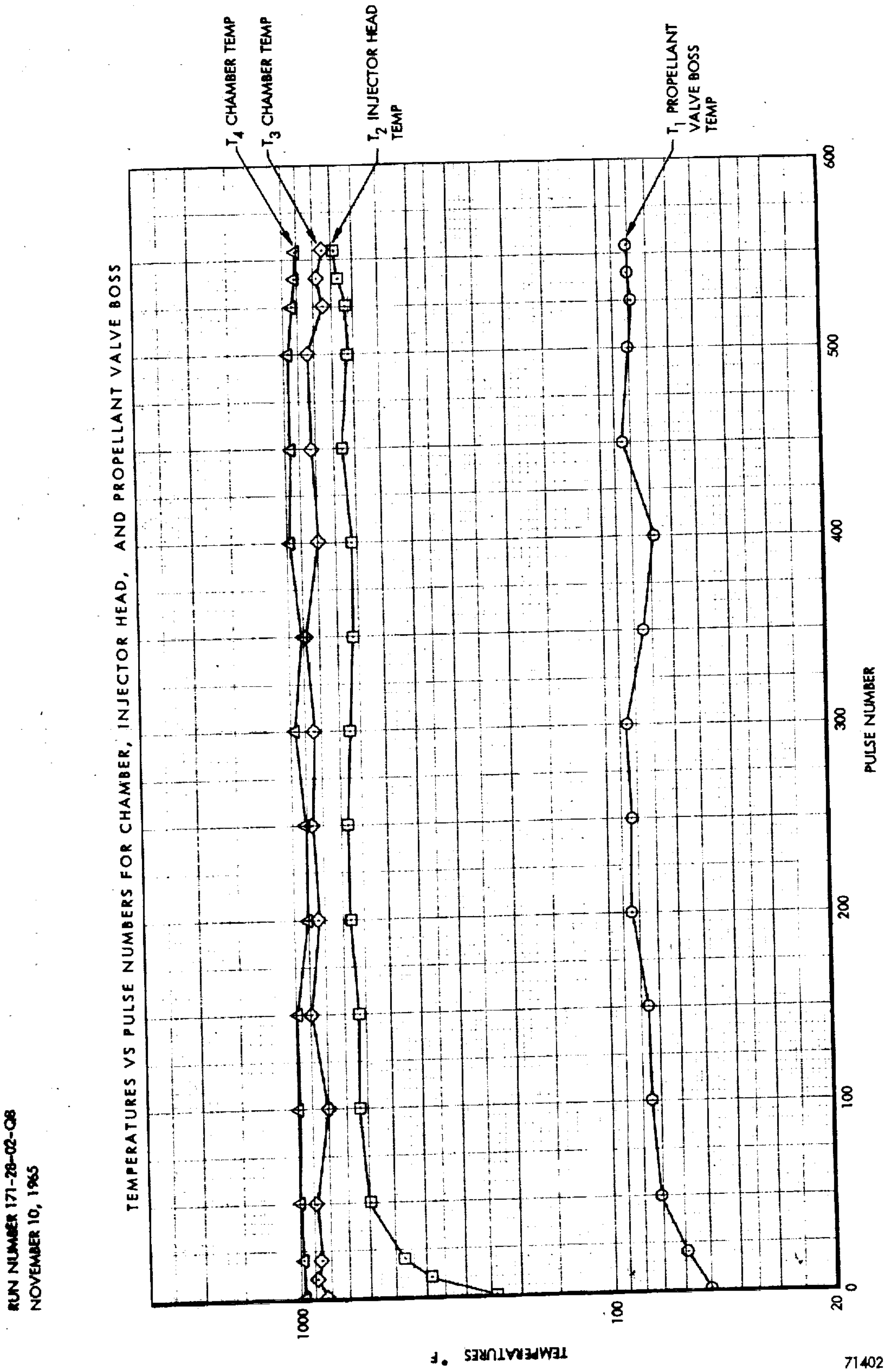

TEMPERATURES VS PULSE NUMBERS FOR CHAMBER, INJECTOR HEAD, AND PROPELLANT VALVE BOSS
RUN NUMBER 171-28-02-Q8
NOVEMBER 10, 1965
T_4 CHAMBER TEMP
T_3 CHAMBER TEMP
T_2 INJECTOR HEAD TEMP
T_1 PROPELLANT VALVE BOSS TEMP
TEMPERATURES °F
1000
100
20
PULSE NUMBER
0
100
200
300
400
500
600
71402

FIGURE 26

TEST RECORD RUN NO. 171-28-01-A2

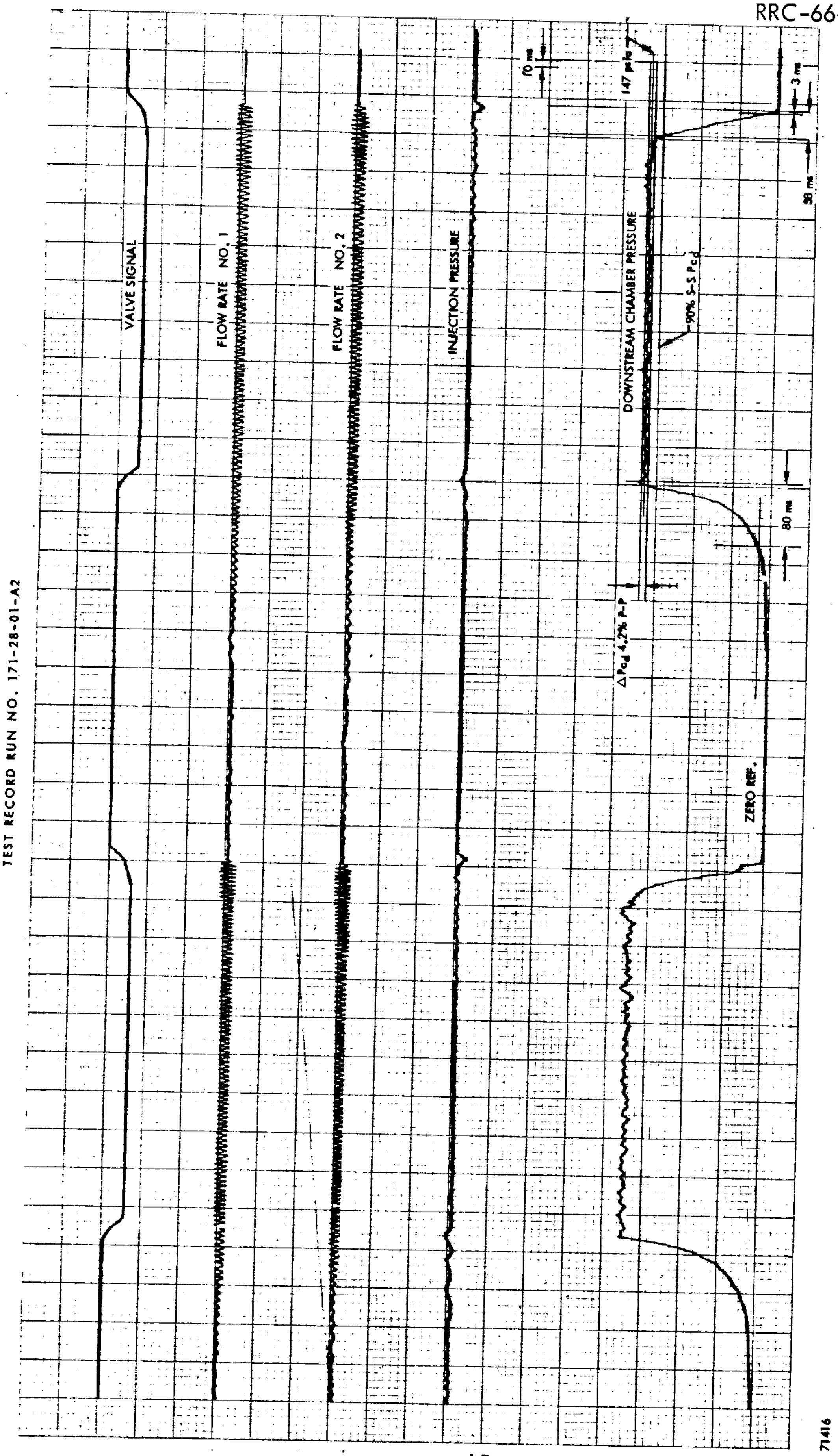
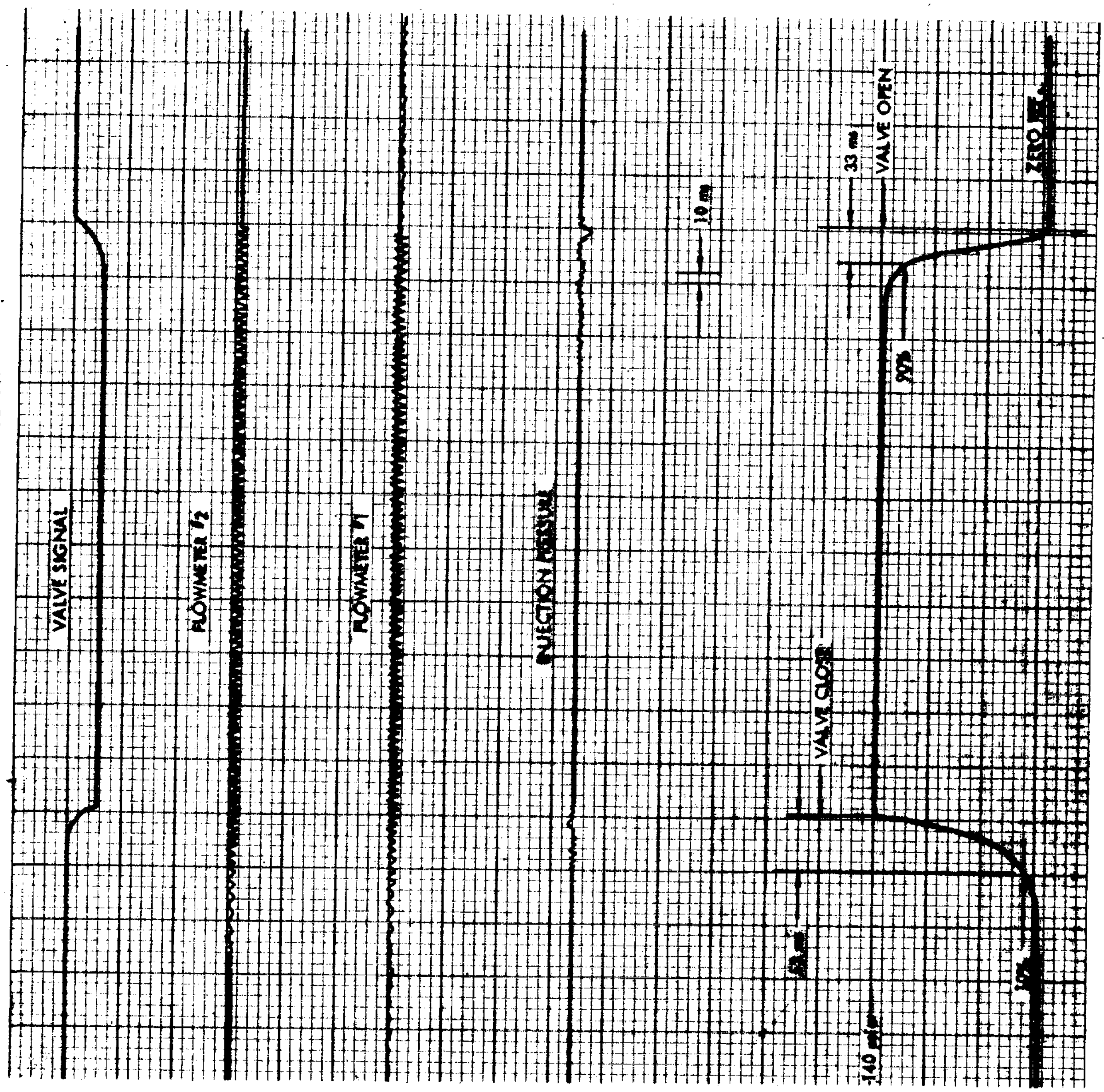


FIGURE 27

PRECEDING PAGE BLANK NOT FILMED.

TEST RECORD RUN NO. 171-28-02-A1



71415

FIGURE 28

.5 lbf N_2H_4 TEST DATA SU

Run No.	Duty Cycle %	Pulse Width sec.	P_{hi} psia	P_{hf} psia	P_{cd_i} psia	P_{cd_f} psia	lbm/sec
171-28-02-A1	100/50	60/.500	273	273	158	158	.002444
171-28-02-A2	100/50	60/.500	270	270	152	152	.002379
171-28-02-Q1	100	300	262.5	168	145	100	N.A.
171-28-02-Q2	50	500	268.5	178.5	150	50	N.A.
171-28-02-Q3		VOID			VOID		
171-28-02-Q4	100	300	262	192	125	95	N.A.
171-28-02-Q5	50	.500	266	182	138	60	N.A.
171-28-02-Q6	20	.300	272	176	146	70	N.A.
171-28-02-Q7	100	300	265	200	150	80	N.A.
171-28-02-Q8	50	.500	282	183	149	67	N.A.
171-28-03-A1	100/50	60/.500	276	274	158.5	158.5	.00234
171-28-03-A2	100/50	60/.500	231	230	140	140	.00212
171-28-01-A1	100/50	60/.500	274	273	157.5	157.5	.00241
171-28-01-A2	100/50	60/.500	277	275	146	146	.00220
171-28-04-A1	100/50	60/.500	275	273	156	156	.00246
171-28-04-A2	100/50	60/.500	267	266	154	154	.00227
171-28-02-A3	100/50	60/.500	267	264	140	140	.00213

TABLE IV

JMMARY (ACCEPTANCE AND PREQUALIFICATION)

T-1 °F	T-2 °F	T-3 °F	T-4 °F	T_h °F	Response to 90% milli-seconds	Tailoff to 10% milli-seconds	Ignition Delay milli-seconds	P_{cd} % P-P	c* ft/sec.	Test Duration seconds
64	309	N.O.	1105	55	1684	77	N.O.	5.18	4090	60
64	N.O.	1350	N.O.	55	2060/35	68/65	22/4	4.4/4.6	4040	70
68	251	1404	1094	60	1510	57	126	4.45	N.A.	300
68	692	1265	1053	51	30 Ave.	65 Ave.	4	1.5	N.A.	600
	VOID				VOID			VOID		
65	550	900	990	50	3380	91	7	4.5	N.A.	300
65	500	780	910	49	33 Ave.	70 Ave.	4 Ave.	4.5	N.A.	600
43	600	700	750	49	30 Ave.	60 Ave.	4 Ave.	3.88	N.A.	1500
N.O.	500	960	1090	48	1467	59	93	4.57	N.A.	300
80	640	875	980	48	30 Ave.	59 Ave.	4 Ave.	6.25	N.A.	600
N.A.	N.A.	N.A.	N.A.	48	1834/35	95/87	20/3	16.5/5.6	4260	70
N.A.	N.A.	N.A.	N.A.	40	1508/37	73/62	17/3	10.6/1.9	4160	70
N.A.	N.A.	N.A.	N.A.	41	1280/42	70/69	12/3	10/5.5	4110	70
N.A.	N.A.	N.A.	N.A.	41	1290/38	88/80	10/3	6.1/4.2	4180	70
N.A.	N.A.	N.A.	N.A.	39	1512/57	80/88	5/5	10/5.5	4010	70
N.A.	N.A.	N.A.	N.A.	39	1318/37	70/70	70/4	23.5/5.7	4240	70
N.A.	N.A.	N.A.	N.A.	45	2250/33	65/52	10/4	.66/.66	4140	70